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**Cryogenic Wind Tunnels for High
Reynolds Number Testing**

**Pierce L. Lawing, Robert A. Kilgore,
and Peggy D. McGuire**

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Cryogenic Wind Tunnels for High Reynolds Number Testing

**Pierce L. Lawing, Robert A. Kilgore,
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Compiled from a lecture series presented at
the University of Tennessee Space Institute

N86-29872 #

INTRODUCTION

This paper is a compilation of lectures presented at various Universities over the span of several years . A central theme of these lectures has been to present the research facility in terms of the service it provides to, and its potential effect on, the entire community, rather than just the research community. This theme is preserved in this paper which deals with cryogenic wind tunnels as a class rather than as a single facility.

The initial section of the paper deals with the relationship between the aerospace marketplace, military and commercial, military necessity, and the study of transonics. Transonic aerodynamics is a focus both because of its crucial role in determining the success of aeronautical systems and because cryogenic wind tunnels are especially applicable to the transonics problem.

The mid-section of the paper provides historical perspective and technical background for cryogenic tunnels, culminating in a brief review of cryogenic wind tunnel projects around the world. The appendix is included to provide up to date information on testing techniques that have been developed for the cryogenic tunnels at Langley Research Center. In order to be as inclusive and as up to date as possible, the appendix tends to be even less formal than the main body of the paper.

It is anticipated that this paper will be of particular value to the technical person who is inquisitive as to the value of, and need for, cryogenic tunnels.

WHY DO WE NEED TRANSONIC TUNNELS ? ? ?

Subsonic commercial passenger aircraft:

Increase the cruise velocity and/or improve fuel efficiency

Helicopters:

- Reduce blade noise
- Improve performance

Supersonic transports and bombers:

- Reduce transonic drag and improve transonic propulsion

Fighter aircraft:

- Provide transonic maneuver capability and reduce drag

Space Shuttle:

- Simulate transonic portion of ascent
- Improve transonic design capability for future shuttle

Computational capability:

- Wind tunnel simulation of flight to verify techniques

UTSI-PLL (5) 1985

This chart lists needs for a transonic tunnel in relation to aeronautical systems. The need for good experimental data in entire disciplinary areas, such as dynamic stability, is only implied. Each system has its own requirements for transonic information. For instance, the subsonic transport aircraft does not of itself fly through this speed range, but induces locally high velocities on the top surface of its wings in order to produce the low pressures that result in the required lift. Well before an aircraft itself reaches transonic speeds, these local flows become transonic and the performance robbing shocks develop. The relatively slow helicopter operates its blades well into the transonic regime, and good transonic blade design is vital to their continued development.

Supersonic transports and bombers must be designed to fly through transonic speeds and cruise at supersonic Mach numbers. Therefore it would be desirable to optimize the design for the higher speed range. However, the vehicle must generate enough thrust to overcome the transonic drag for the brief time it flies there or it will never get to supersonic speeds. This thrust greater than drag crisis is further complicated by transonic performance losses in the propulsion system. These penalties could add to determine the engine size, and the vehicle may have to carry an oversize engine that is required only to accelerate through the transonic regime. In actual practice, an optimum mix between engine design, vehicle transonic drag, and climb trajectory is required.

Supersonic fighter aircraft must be designed not only to traverse the drag rise in a manner similar to the supersonic transport, but also to maneuver and fight transonically opening a new science of transonic vehicle dynamics and control. Store separation at transonic speeds is presently a fledgling art, limiting the design envelope of air launched missiles, pilot ejection, supply drops, and fuel tank jettison.

Ground launched space vehicles like the Space Shuttle incur transonic penalties not only from the drag losses, but also from loads induced on their relatively delicate structures from the strong, sometimes rapidly moving transonic shock systems.

From the preceding discussion it is evident that careful design work is necessary for efficient aerodynamic systems that are required to fly in the transonic regime. This demanding science requires the very best we can offer in both analytical techniques and experimental facilities. The new cryogenic wind tunnels are already proving themselves as valuable tools for the study of transonic aerodynamics. The two cryogenic wind tunnels currently performing transonic research in the U. S. are the 0.3-m Transonic Cryogenic Tunnel, and the National Transonic Facility or NTF.

**EXPORTS OF U.S. AEROSPACE PRODUCTS
(CALENDAR YEARS 1977-1981)**

(Millions of Dollars)

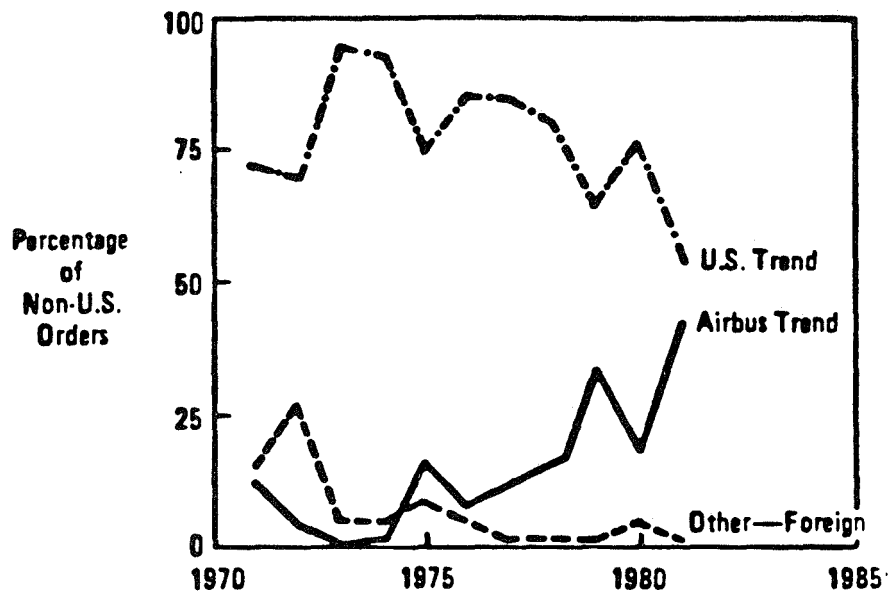
	1977	1978	1979	1980	1981	Annualized Growth Rate
<u>Grand Total</u>	7,581	10,001	11,747	15,506	17,634	.23
<u>Total Civil</u>	5,049	6,018	9,772	13,248	13,312	.27
Complete Aircraft	2,747	3,625	6,177	8,256	8,613	.33
Aircraft Engines	233	277	375	556	784	.35
Parts, Accessories, and Equipment	2,069	2,116	3,220	4,436	3,915	.17
<u>Total Military</u>	2,532	3,983	1,975	2,258	4,322	.14
Complete Aircraft	1,186	2,243	838	949	1,712	.10
Aircraft Engines	71	61	67	63	83	.04
Parts, Accessories, and Equipment	826	1,044	467	497	1,971	.24
Rockets, Guided Missiles, and Parts	449	635	603	749	556	.05

Economic Need for Transonic Capability

The table presented here was taken from "Aeronautical Research and Technology Policy", Executive Office of the President, Office of Science and Technology Policy, November 1982. This data shows that, in 1981, just the exports from the aerospace business in this country totaled more than 17 billion dollars. Note that 13 billion, or 75% of this total, was generated by civil aircraft. If the growth rate of 0.23 shown here is applied to the 17 billion dollar total to update it to 1985, the result is in excess of 40 billion dollars. This volume of business is large enough to be important to any economy, but it is particularly important to a nation suffering an imbalance in trade.

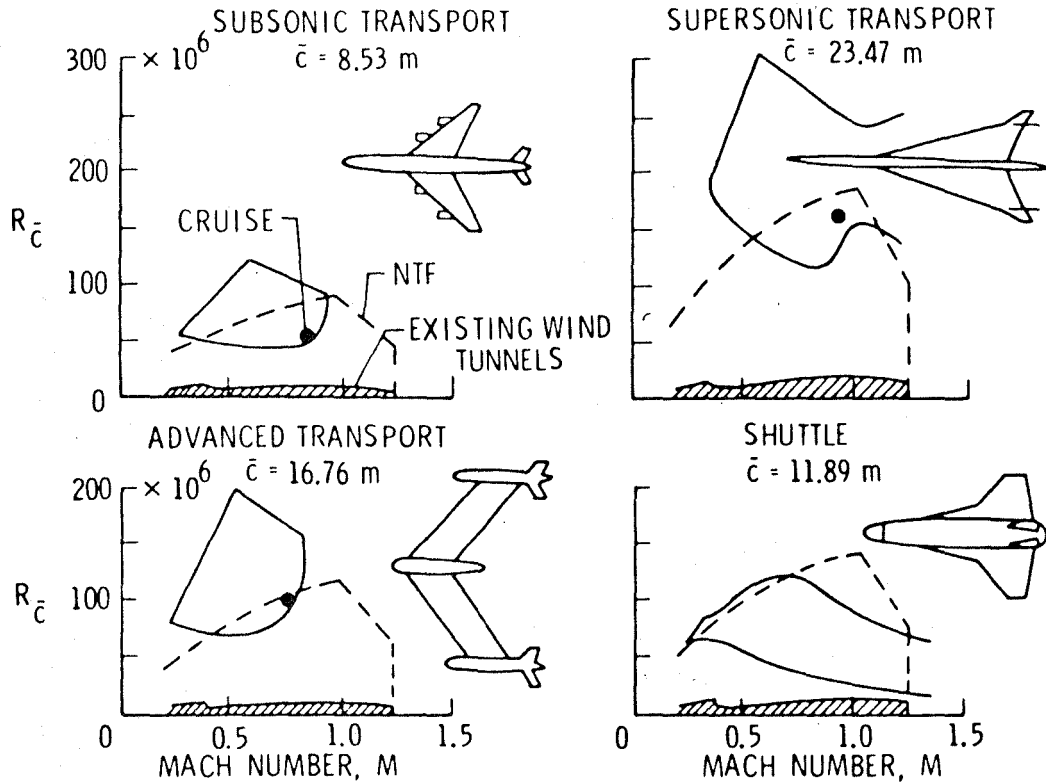
One of the salient factors in maintaining a competitive edge in each of these systems is superior performance in the transonic area. This is especially potent for the commercial transport where a 1% increase in speed means one extra flight per hundred flights due to decreased turnaround times. This extra flight is very profitable compared to the system it replaces, and other factors being equal, the 1% speed margin will sell the new system instead of its competitor. Advances in structures and other areas may improve overall performance, but an improvement in transonic design, particularly airfoil design, is a direct and powerful influence on profitability.

CIVIL TRANSPORT AIRCRAFT MARKET POSITION



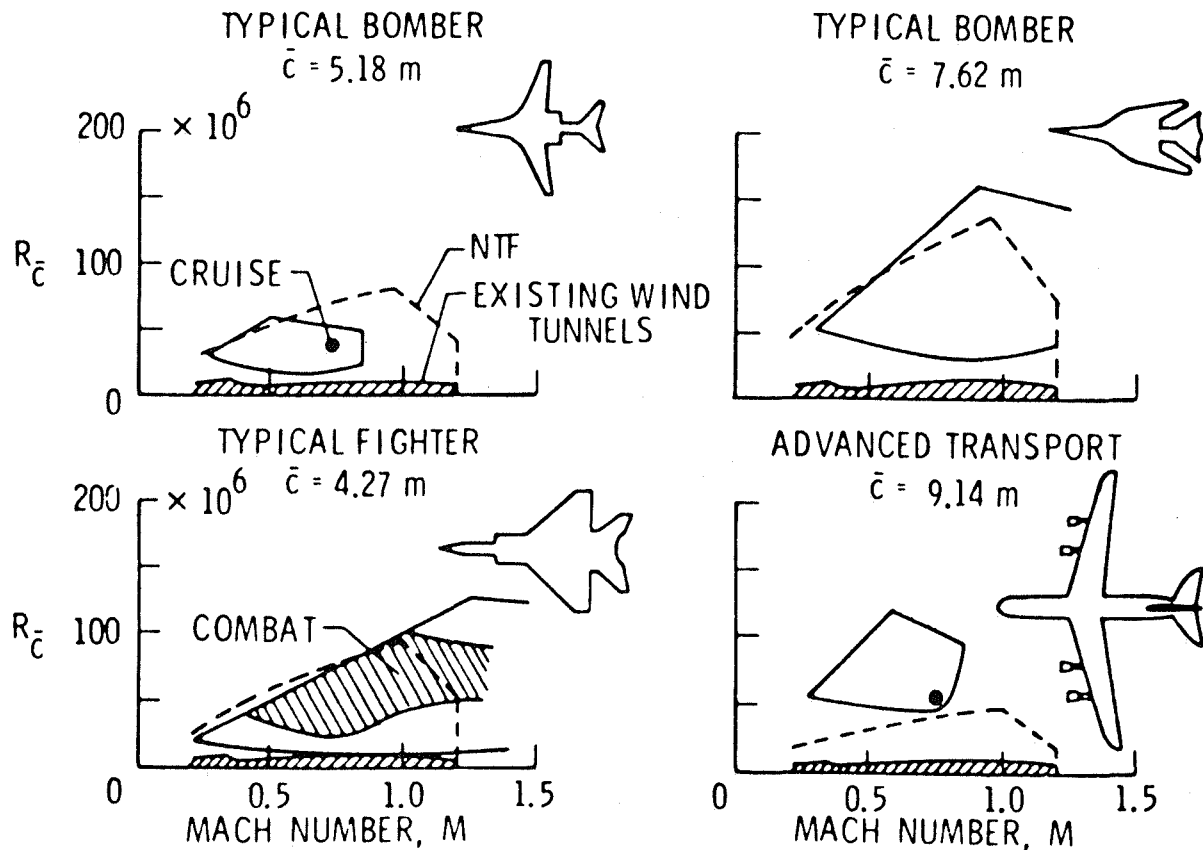
Competitive Position in Transonic Airfoil Designs

This chart shows a disturbing trend of increasingly effective foreign competition for sales outside the U. S. market. Although a host of factors not related to aircraft performance affect these sales trends, it is obvious that diligence in improving our technology will be necessary to reverse this trend. This chart is taken from the same 1982 source as the previous one, but continuing concern may be perceived in this quote from the White House Aeronautical Policy Review Committee; "Advanced technology for a new generation of fuel-efficient, affordable U. S. subsonic aircraft will be the highest priority in U. S. aeronautical policy." Taken from *Aviation Week & Space Technology*, April 8, 1985. The new high-Reynolds number, cryogenic tunnels will be a valuable tool in the design of this new aircraft.



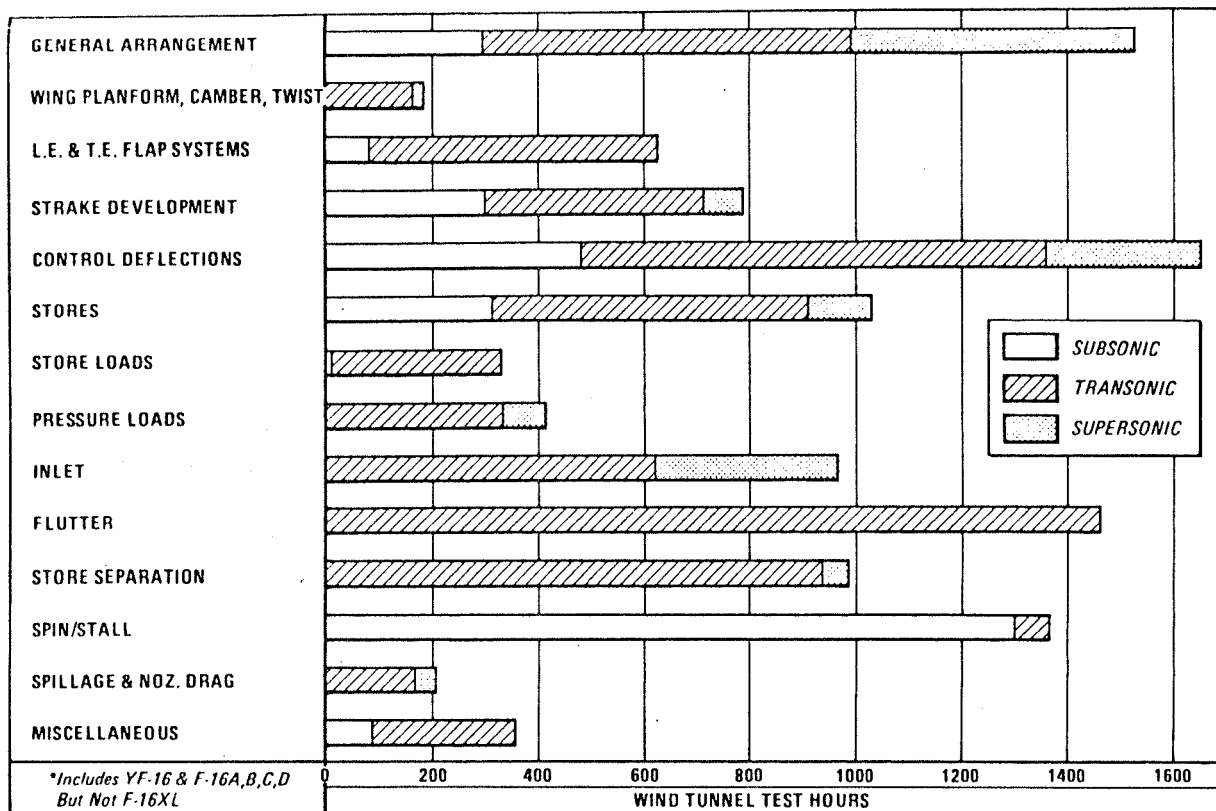
Cryogenic Tunnel Capabilities For Civilian Aircraft

The enhanced capability of the National Transonic Facility, NTF, is compared here with non-cryogenic tunnels and the requirements of four typical aircraft systems. The aircraft requirements are presented in terms of Reynolds number based on a representative wing chord length, and as a function of Mach number from zero through transonic. The flight envelope of each aircraft is bounded by a solid line, and the NTF capability is bounded by the dashed line. Conventional wind tunnels are represented by the shaded areas. The only configuration fully serviced by even the NTF is the Shuttle, but the very important cruise point for the other vehicles is covered.



Cryogenic Tunnel Capabilities For Military Aircraft

The enhanced capability of the National Transonic Facility, NTF, is compared here with non-cryogenic tunnels and the requirements of four typical aircraft systems. The aircraft requirements are presented in terms of Reynolds number based on a representative wing chord length, and as a function of Mach number from zero through transonic. The flight envelope of each aircraft is bounded by a solid line, and the NTF capability is bounded by the dashed line. Conventional wind tunnels are represented by the shaded areas. As in the previous slide, the conventional tunnels are inadequate in providing flight values of Reynolds number, whereas the NTF covers most of the flight envelope for the bombers and fighters, and nearly matches the cruise point for a heavy transport. Note especially that the very important combat envelope of the fighter is well covered in the transonic range.



F-16 Wind Tunnel Test Summary (1971-1982).*

Transonic Wind Tunnel Tests Required

This chart presents a breakdown of the wind tunnel testing program required in the development of one of our current fighter aircraft. The breakdown is by aerodynamic discipline and for subsonic, transonic, and supersonic speeds. Note that roughly half of the total test program was devoted to transonic flow. Nearly all of the transonic data had to be obtained at Reynolds numbers that were much too low. Although the use of devices such as boundary layer trips can cause premature turbulence and simulate the effects of higher Reynolds number flow, the confidence in the results will be much higher in the future due to cryogenic transonic tunnels operating at the flight Reynolds number. Improved data should lead not only to more optimum designs, but should also decrease the wind tunnel occupancy time, decrease the test program cost, and bring the final system more quickly to fruition.

Cryogenic Wind Tunnels for High Reynolds Number Testing

- * Why we need wind tunnels*
- * Problems with wind tunnels*
- * Possible solutions*
- * Advantages of cryogenic tunnels*
- * The cryogenic solution realized*
- * What's next?*

UTSI (5) 1985 pdm

This portion of the paper is intended to provide an overview of the evolution and early development of cryogenic wind tunnels, a status report on some of the cryogenic wind tunnel activities around the world, and finally, a brief look at some developments aimed at further improving the testing capabilities of wind tunnels. This chart shows in outline form the areas to be covered.

The first item could be worded, "Why do we need wind tunnels?" This is a legitimate question in this age of computers and ever-improving techniques in computational fluid dynamics. The wording, "Why we need wind tunnels", betrays to some extent an experimental background and, hopefully more importantly, reflects the fact that many complex three-dimensional flows cannot yet be adequately dealt with analytically.

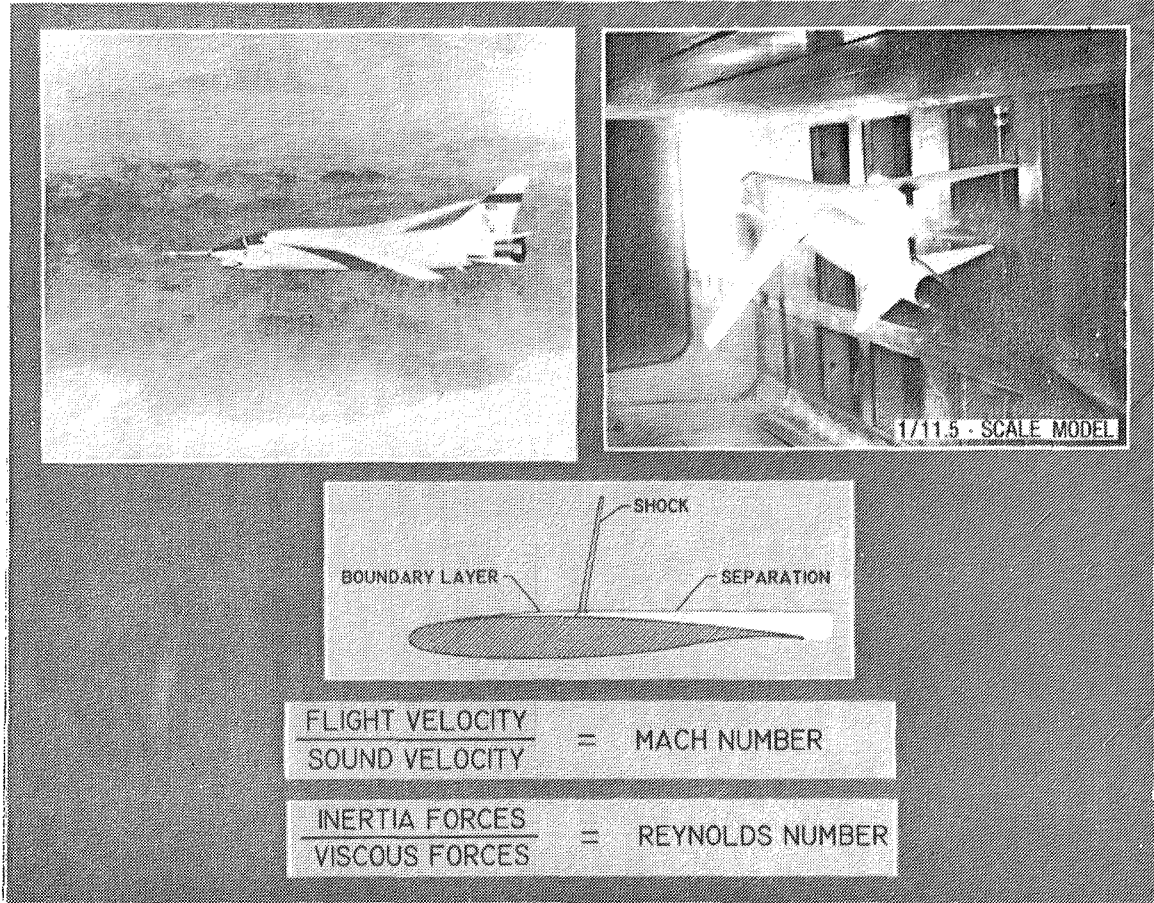
Although wind tunnels are less than perfect on several counts, our interest at the moment is the fact that for most wind tunnel tests the Reynolds number is much too low, often by an order of magnitude or more.

This paper touches very briefly on some possible solutions to the problem of low Reynolds number in order to introduce what appears to be the best solution, that is, operating the tunnel at cryogenic temperatures (arbitrarily defined as temperatures of 150 K (-190 F) or less).

The major portion of this paper will be devoted to a review of the theory and advantages of Cryogenic Tunnels and a brief description of the various applications of the Cryogenic Tunnel concept around the world.

And, finally, it will take a brief look into the future and describe some emerging technologies that promise to have a very favorable impact on wind tunnel testing.

FLOW SIMILARITY PARAMETERS



This figure is intended to illustrate that you can, at least in theory, use a sub-scale model in a wind tunnel to determine the aerodynamic forces and moments and the pressure distributions experienced by the full-scale vehicle in free flight.

To achieve "flow similarity" between the vehicle in flight and the model in the wind tunnel at speeds where compressibility effects are important, it is necessary to match both Mach number and Reynolds number.

Matching Mach number is relatively easy, even at transonic speeds, if the walls of the test section are ventilated or, in the case of solid walls, if they are suitably contoured. However, matching flight values of Reynolds numbers in a wind tunnel, especially at transonic speeds, is much more of a problem, as we will see later.

These photographs also illustrate two other problems common to most wind tunnel testing. First, there is the close proximity of the test-section walls to the model. The second problem arises from the use of model support systems, such as the "sting" shown here, which usually require alterations to the desired model geometry as well as produce changes in the flow field near the model.



Before we go any further, let's pause briefly to pay our respects to the gentleman who, so far as we can tell, was directly responsible for the building of the very first wind tunnel.

The origin of all wind tunnels is to be found in a very simple tunnel built one hundred and fifteen years ago in Greenwich, England. It was in 1870 that the first wind tunnel was built for the Aeronautical Society of Great Britain under the direction of a marine engineer with a keen interest in aeronautics, Mr. F. H. Wenham.

No photograph or detailed description of this historic tunnel has been found and we can only speculate on its appearance. The only description we have is the following: "By means of a fan-blower, a current of considerable force was directed through a trunk ten feet long by eighteen inches square."

Sixth Annual Report
of the
AERONAUTICAL SOCIETY of GREAT BRITAIN
For the Year 1871

EXPERIMENTAL FUND

Henry Wright, Esq., Stafford House, St. James, *Treasurer.*

Donors	£.	s.	d.
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As perhaps an interesting aside, we note that the first wind tunnel was built and the first wind-tunnel data was obtained (on a series of "inclined planes") by the aid of a special subscription collected from Members of the Aeronautical Society (later changed to the Royal Aeronautical Society).

The table shown above, taken from the Sixth Annual Report of the Aeronautical Society (for the year 1871), lists the Donors and the amount of their contribution to the Experimental Fund. At least in terms of financing aeronautical research, life seems to have been simpler and more straight forward in the 1870's than in the 1980's.

Problems Common to Wind Tunnels

1920

Low Reynolds number

Flow unsteadiness

Wall interference

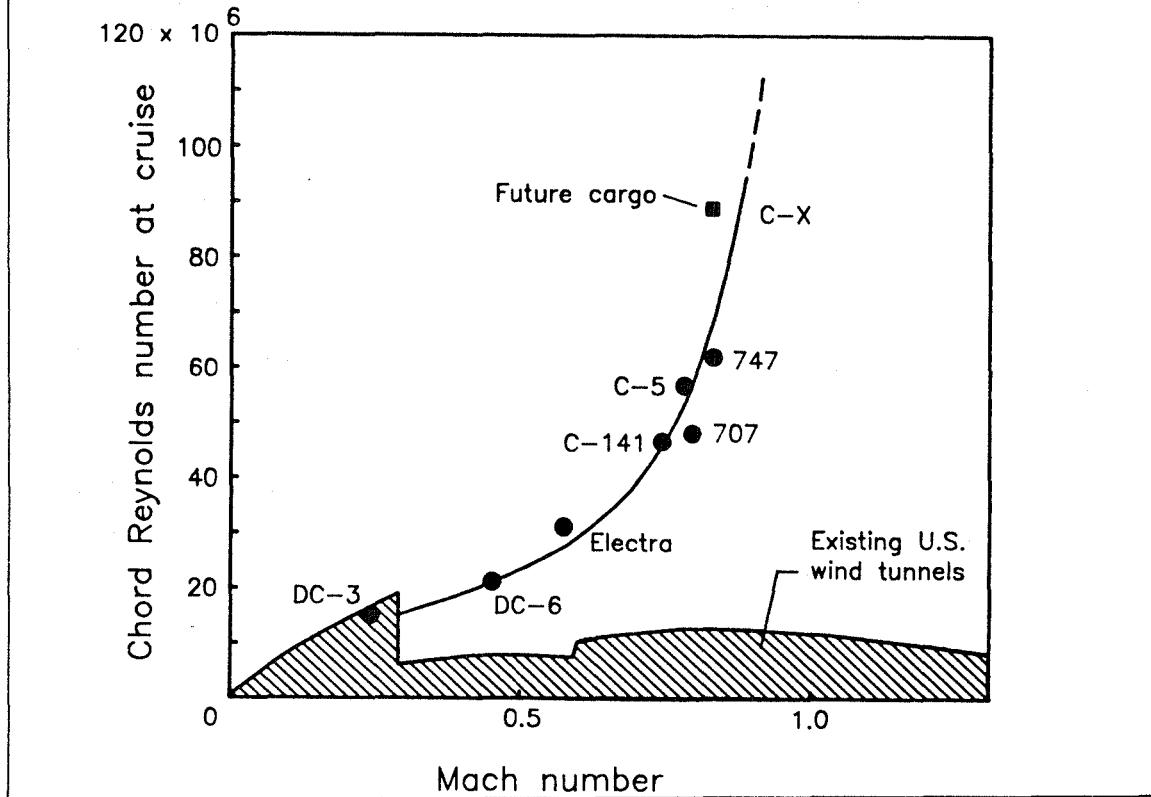
Support interference

ABRL pdm 5-2-24

In several of the aeronautical papers written around 1920, the "problems" shown on this chart were listed as common to even the best wind tunnels of that era. As you can see, the major problems we have with the wind tunnels of today were also recognized in the wind tunnels of 65 years ago. It is only fair to note that these problems are still with us not through a lack of effort in trying to solve them during the last 65 years. Rather, they are still with us due to their complexity as well as to the fact that, with some, their magnitude and nature have changed with increasing flight speed and aircraft size. Thus, we find that many of the solutions that were developed and found to be adequate at low speeds are of little or no use today.

Each of the "problems" shown on this chart could easily be the subject of a whole series of papers. However, as previously stated, this paper deals mostly with the single problem of "Low Reynolds number" and what has and is being done about its solution.

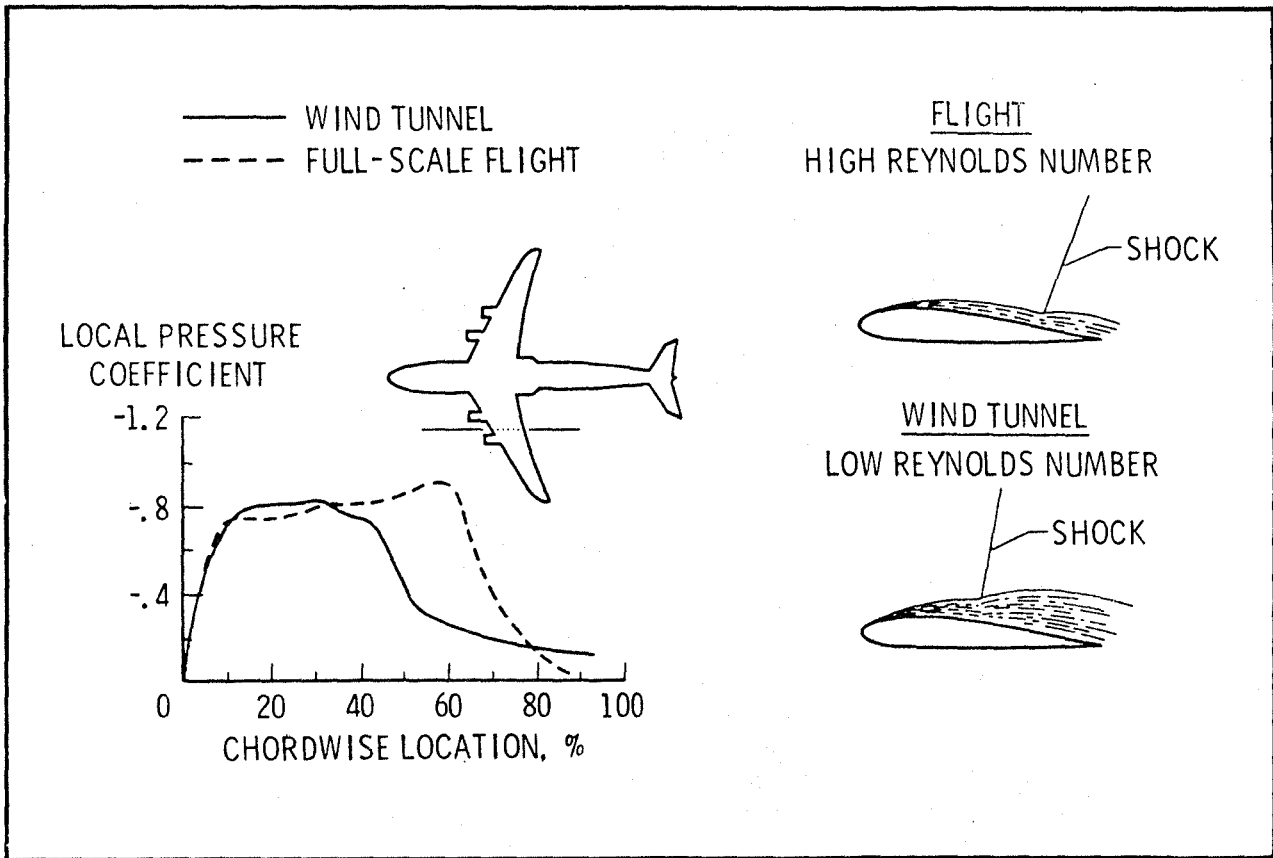
The Growing Reynolds Number Gap



The problem of low test Reynolds number is especially acute at transonic speeds where the large drive-power requirements of transonic tunnels have dictated the use of relatively small tunnels and problems associated with high model loads have limited tunnel operating pressure. With ever increasing aircraft size, existing transonic tunnels are becoming even more inadequate in test Reynolds number capability creating the so-called "Reynolds number gap", the difference between our present wind tunnel capability and full-scale Reynolds number.

The Reynolds number gap in the U. S. at subsonic and transonic speeds is illustrated on this figure which has become somewhat of a classic due to the many times it has been used to illustrate the need for improved wind tunnel capability. As can be seen the Reynolds number gap has been steadily increasing as aircraft have been developed which are larger and fly faster.

C-141 Flight - Wind Tunnel Correlation



Perhaps the best known example of a problem due to scale effect, and one that will illustrate the nature of the problem in general, is that of the C-141 aircraft. In this case, the relatively thicker boundary layer of the low Reynolds number tunnel tests caused the recompression shock to be located 20 percent farther forward on the wing of the model than on the wing of the aircraft in flight. As a result of this lack of proper simulation of flight Reynolds number in the wind tunnel, there was a 9-month delay in the initial operational availability of the C-141.

Four Ways to Increase Reynolds Number

$$\text{Reynolds number} = \frac{\text{Inertia force}}{\text{Viscous force}} = \frac{\rho V^2 l^2}{\mu V l} = \frac{\rho V l}{\mu}$$

Use a heavy gas	Increase ρ Decrease V and μ
Increase model size	Increase l
Increase pressure	Increase ρ
Decrease temperature	Increase ρ Decrease V and μ

NTF-5 pdm 12-5-83

The four ways of increasing the test Reynolds number in a wind tunnel are shown on this chart. Reynolds number is defined as the ratio of inertia to viscous force. Cancelling terms gives the familiar form of the equation for Reynolds number where

ρ = density

V = velocity at free-stream conditions

μ = viscosity

l = measure of model or test section linear dimension

At a given Mach number, the Reynolds number may be increased by using a heavy gas or mixture of gases rather than air as the test gas, by increasing the size of the model, by increasing the operating pressure of the tunnel, or by reducing the test temperature. The method chosen to increase Reynolds number will, in general, also affect dynamic pressure, mass flow rate, and the power consumption of the tunnel per unit of run time.

The use of a heavy gas is a well-known method of achieving high Reynolds number. For example, the use of Freon-12 as a test gas rather than air can result in a significant increase in test Reynolds number while reducing both dynamic pressure and drive power. However, the ratio of specific heats, γ , for Freon-12 is considerably different from that for air ($\gamma = 1.40$ and 1.13 for air and Freon-12, respectively, at standard conditions). Apparently the consequences of this are small in subsonic flow and where effects do exist, there are techniques for correcting the data. However, data obtained in Freon-12 does not agree with data obtained in air when compressibility effects become significant.

Mixtures of gases can be chosen which offer advantages over air while maintaining γ for the mixture close to that for air. One such mixture is Freon-12 with argon. However, it can be shown that the advantages in wind-tunnel design that would result from the use of this mixture would be relatively small.

One of the most straightforward methods of increasing test Reynolds number is to increase the size of the model. However, if l is taken to be a measure of model linear dimension, the test section area, A , must increase as the square of l if tunnel wall interference effects are to be kept constant. Since drive power requirements vary as test section area, drive power will also increase as the square of l . The increases in capital and operating costs are serious problems associated with this method of increasing Reynolds number.

From the point of view of capital and operating costs, it is better to increase Reynolds number by increasing the operating pressure rather than by increasing the size of the model and the tunnel. However, the accompanying increase in dynamic pressure will produce, in relation to a low pressure tunnel, increases in balance and model loads and stresses, reductions in test lift coefficient capability, and increases in support sting interference and aft fuselage distortion, to mention just a few of the problems related to high pressure operation.

Of the various ways of increasing Reynolds number that have been tried or proposed for transonic tunnels, cooling the test gas to cryogenic temperatures (150 K or less) appears to be the best solution in terms of model, balance, and model support loads, as well as capital and operating cost. In addition, as will be described later, having temperature as an independent test variable offers some new and unique testing capabilities which may be of equal importance with the ability to achieve full-scale Reynolds number.

It is useful to examine the underlying mechanism through which changes in pressure and temperature influence Reynolds number. To the first order, μ and the speed of sound, a , and for constant Mach number, the velocity V , are not functions of pressure, while ρ is directly proportional to pressure. Thus, increasing pressure results in an increase in Reynolds number by increasing the inertial force with a commensurate increase in model, balance, and model support loads. Also, to the first order, the dependence on temperature T is given by $\rho \propto T^{-1}$, $V \propto T^{0.5}$, and $\mu \propto T^{0.9}$. Thus, decreasing the temperature of the test gas leaves the inertial force unchanged at a given Mach number due to the compensating effects of ρ and V^2 . Increase in Reynolds number with decreasing temperature is thus due strictly to the large reduction in the viscous force term as a result of changes in μ and V with decreasing temperature.

Variable Density Tunnel Concept

In 1920, Max Munk proposed using compressed air as a way of increasing R by increasing density, ρ .

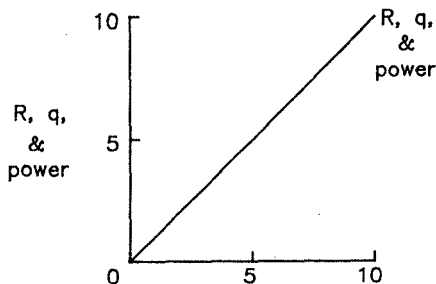
$$* R = \frac{\text{inertia force}}{\text{viscous force}} = \frac{\rho V^2 l}{\mu V l} = \frac{\rho V l}{\mu}$$

$$* \text{Model loads} \propto q = \frac{\rho V^2}{2}$$

$$* \text{Tunnel power} \propto qV = \frac{\rho V^3}{2}$$

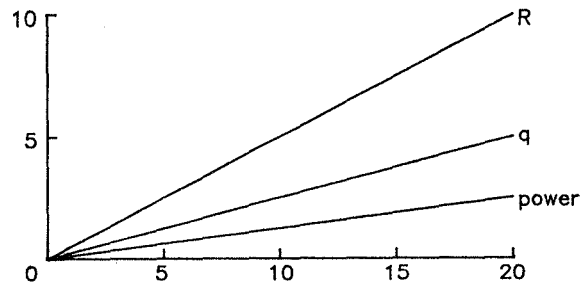
Obvious way

- * Model = 0.1 x full scale
- * Velocity = Flight velocity
- * Pressure = 10 atm



Munk's (better) way

- * Model = 0.1 x full scale
- * Velocity = 0.5 x flight velocity
- * Pressure = 20 atm



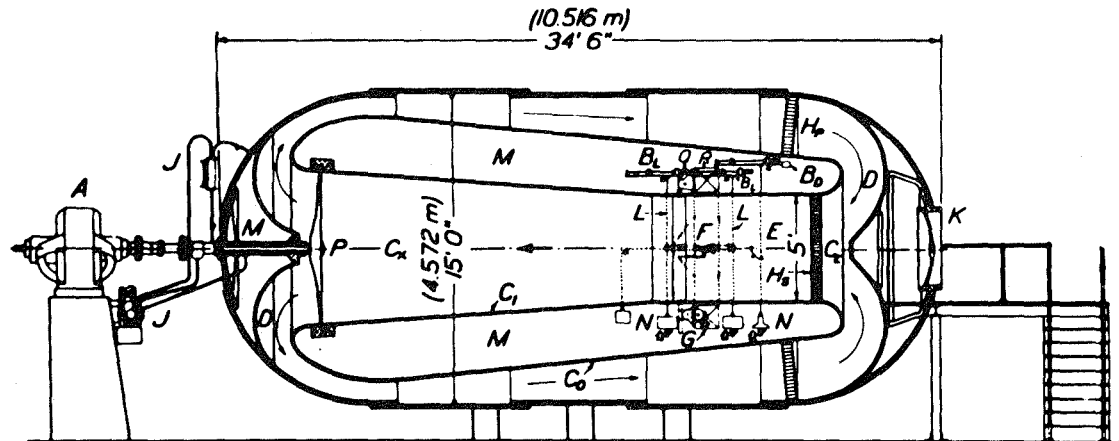
DFVLR11, DAD 7-25-83

A practical solution to the problem of low Reynolds number for low speed tunnels was conceived early in 1920 by Dr. Max Munk at Langley when it was the Langley Memorial Aeronautical Laboratory of the N. A. C. A.

After considering many fluids that might be substituted for air in a wind tunnel in order to increase the test Reynolds number, Munk decided the only reasonable choice would be the "new" fluid he would obtain by compressing air. This new fluid, compressed air, has increased density but essentially unchanged viscosity and speed of sound.

As can be seen from this chart, any increase in Reynolds number brought about solely through pressurization is a result of increasing the inertial force term of the equation for Reynolds number. As shown in the lower left of the chart, the problem with this solution is the fact that the desirable increase in Reynolds number is accompanied by a commensurate and undesirable increase in drive power and in dynamic pressure, q , with increases in model, balance, and sting loads. Munk circumvented to some extent the problem of increased power and q by taking advantage of the fact that Mach number did not have to be matched between the tunnel tests and the full-scale low-speed airplanes of the 1920's. As shown in the lower right of the chart, Munk recognized that testing 0.1-scale models at a pressure of 20 atmospheres and at one half of the full-scale speed made it possible to achieve full-scale values of Reynolds number with drive power increased by a factor of only 2.5 and model loads only a factor of five over those experienced in conventional unpressurized tunnels.

SECTIONAL ELEVATION OF VARIABLE DENSITY WIND TUNNEL



A-Synchronous motor
 B-Lift balance
 B_d-Drag balance
 C_e-Entrance cone
 C_e-Exit cone
 C_o-Outer cone
 C_i-Inner cone

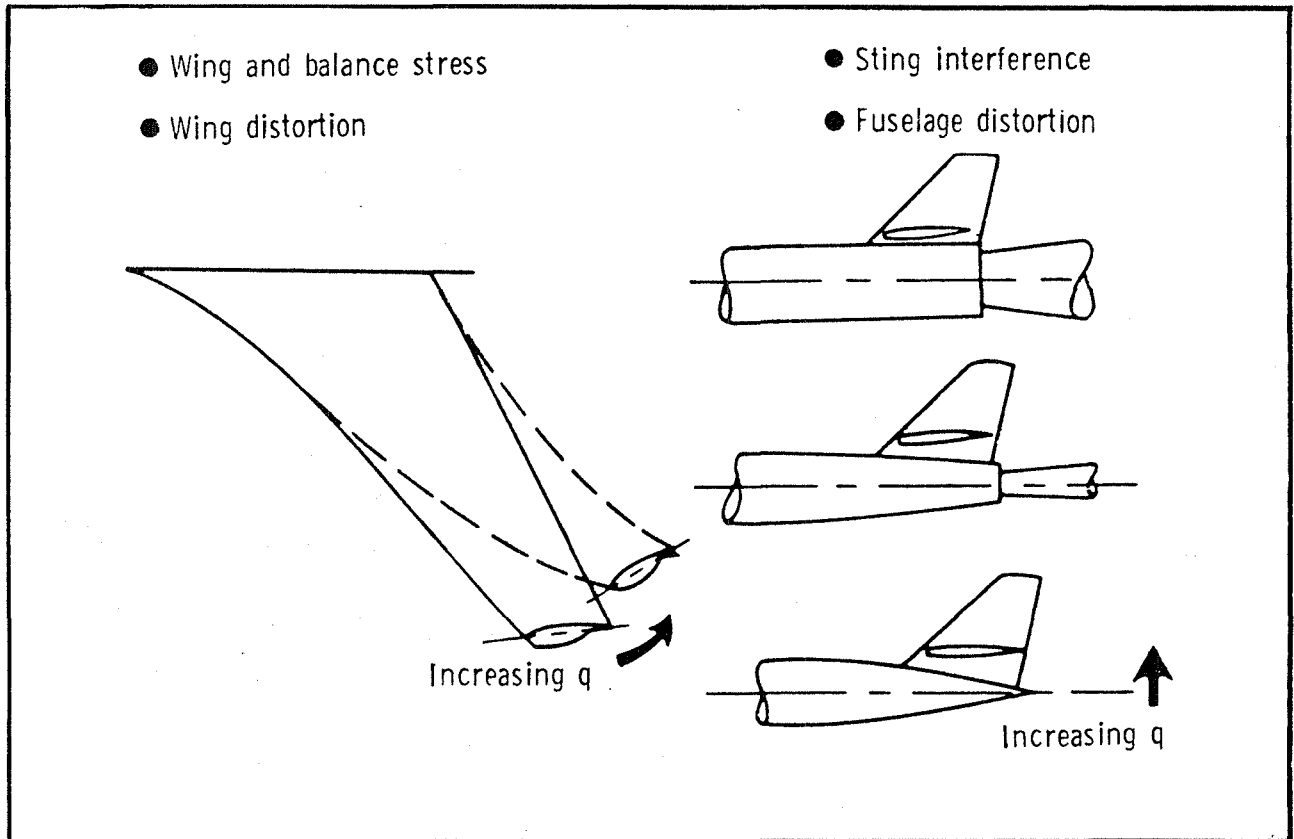
D-Deflector
 E-Experiment chamber
 F-Model
 G-Angle of attack mechanism
 H_p-Primary ring honeycomb
 H_s-Secondary honeycomb
 J-Oil-seal mechanism

K-Door
 L-Vertical rod
 M-Dead-air space
 N-Weight
 P-Propeller, 2-blade, 7 ft
 Q-Revolution counter
 R-Balance ring



Munk's suggested solution to the problem of low Reynolds number was realized in 1921 with the construction of the second wind tunnel at Langley Field, the N. A. C. A. variable density wind tunnel (VDT). A sectional view and a photograph of the VDT are shown above. The influence of the high operating pressure is evident in the design of the annular-return tunnel within the very sturdy pressure vessel.

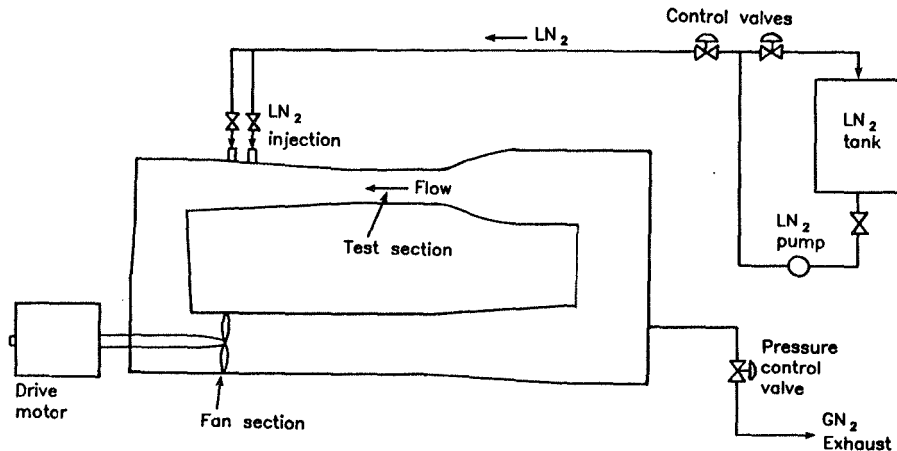
Some Problems with High Dynamic Pressures



When compressibility effects become important, both flight Reynolds number and flight Mach number must be matched in the wind tunnel. Thus, for much of today's testing, we are not able to take advantage of Munk's idea of simply reducing velocity in order to keep power and dynamic pressure within reasonable bounds. Some of the problems that can arise when excessively high pressure is used to increase test Reynolds number are illustrated in the chart shown above.

In addition to increasing wing deflection with increasing q , it may be necessary to drastically modify the shape of the aft portion of the model fuselage to accommodate the more robust support sting. Also, the larger sting can seriously distort the flow field. To avoid these problems, high test pressures are generally not used except for tests at very low speeds.

Typical Cryogenic Wind Tunnel



Although design and operational details of some existing cryogenic wind tunnels will be presented later, it may be helpful at this stage to introduce a "notional" cryogenic wind tunnel in order to illustrate the concept.

While the benefits of cryogenic operation can be realized with most types of wind tunnels, the continuous-flow fan-driven tunnel will be used to illustrate the concept because it is particularly well suited to take full advantage of operating at cryogenic temperatures.

Shown in the above figure are the essential elements of a typical fan-driven tunnel capable of operation at cryogenic temperatures. Shown in schematic form is the wind tunnel with its drive fan and motor. For cryogenic operation, we must add to the tunnel structure suitable thermal insulation and sufficient plumbing to allow the injection of liquid nitrogen for cooling and the venting of the resulting gaseous nitrogen. With this scheme, the test gas is nitrogen rather than air, a difference, as can be shown, of no aerodynamic consequence.

Evolution of the Cryogenic Wind Tunnel

* F. H. Wenham, 1870

* W. Margoulis, 1920

* R. Smelt, 1945 (1978)

* M. J. Goodyer, 1971

The above chart lists people and dates of significance to the evolution of the cryogenic wind tunnel.

Wenham's obvious contribution in building the first wind tunnel has already been discussed.

The idea of actively cooling the test gas of a wind tunnel in order to increase its Reynolds number capability appears to have been first proposed in 1920 when W. Margoulis, a Frenchman working as an "aerodynamical expert" in the Paris Office of the U. S. National Advisory Committee for Aeronautics, NACA, pointed out that using a heavy gas, such as carbon dioxide, and cooling the gas to 253 K would increase the test Reynolds number and reduce the drive power requirements for fan driven tunnels.^{9,10} Margoulis and other researchers of that time concluded that the moderate increase in Reynolds number resulting from cooling to 253 K was not worth the effort, and so far as we know, no attempt was made at that time to cool the test gas in a wind tunnel below ambient conditions.

As with many good ideas, that of cooling the test gas in order to increase Reynolds number seems to have been independently recognized and proposed by several people before finally being put into practice.

Margoulis' idea of 1920 appears to have been forgotten, or at least not mentioned in print, until some 25 years later when, in 1945, a theoretical study by Smelt again pointed out that the use of heavy gases and reduced temperatures would permit large reductions in wind-tunnel size and power requirements in comparison with a wind tunnel operated at normal temperature and the same pressure, Mach number, and Reynolds number.¹¹ The study by Smelt was presumably a case of the independent re-invention, since Margoulis was not cited. During a visit to Langley in 1975, Dr. Smelt stated that the lack of a practical

means of cooling a reasonably sized wind tunnel to cryogenic temperatures and the unavailability of suitable structural materials precluded application of the cryogenic wind-tunnel concept at the time of his study.

The apparent lack of interest in overcoming these practical problems and applying the cryogenic concept in 1945 was probably due to the fact that the Reynolds number gap was not as great in 1945 as it is today, since aircraft of that time were generally smaller than those of today and were not being designed to operate with local transonic flows. It also appears that the excellent study by Smelt did not, in later years, receive the wide recognition it deserved due to its security classification. Smelt's paper was, in fact, finally declassified and made available to the public in 1978, 33 years after it was written!

Means for Generating High Reynolds numbers
on models in wind tunnel facilities.

*The basic notion is to use in the
tunnel a gas, such as air, cooled to a temperature
which is well below room temperature. The lower the
air temperature, the higher the Reynolds number at
constant Mach number, model size, and working
section total pressure.*

.

*. The costs of a Magnetic Balance and Suspension
System for wind tunnel models rise
rapidly with tunnel size. The use of a cooled
working fluid may allow relatively high Reynolds
numbers to be achieved with acceptable facility costs.*

M. J. Goodyer

October 27th 1971

Witnessed and understood
Witnessed and understood

Robert A. Kilgore, October 27th 1971
Jerry B. Adcock, October 28, 1971

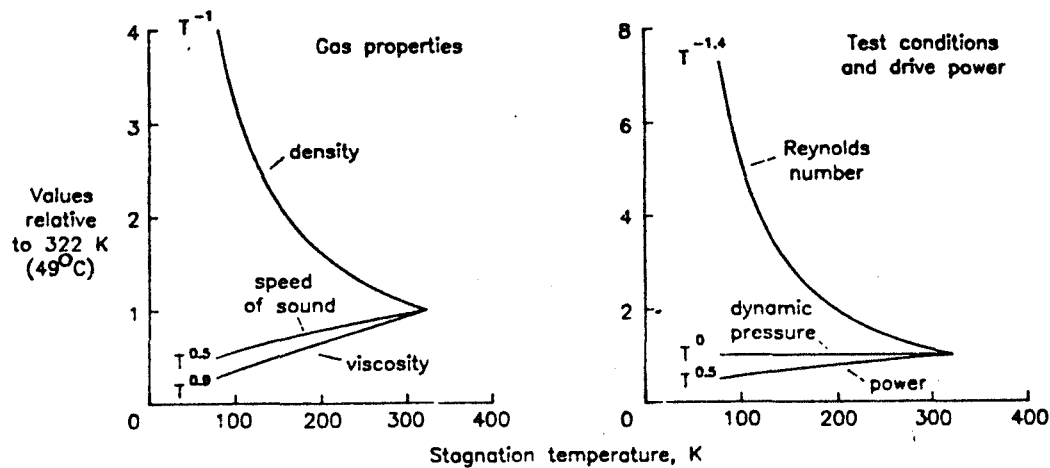
The next step in the evolution of the cryogenic wind tunnel took place at the Langley Research Center in October 1971. Dr. M. J. Goodyer of the University of Southampton, England, who was working at Langley at the time, independently suggested the use of either air or nitrogen at cryogenic test temperatures as a way of increasing the test Reynolds number in the small tunnels equipped with magnetic-suspension and balance systems. By 1971, the availability of liquified gases in large quantities and the widespread application of cryogenic technology in government and industry made Goodyer's proposal seem reasonable not only for the tunnels of modest size equipped with magnetic suspension and balance systems, but also for large tunnels that would be capable of testing models at full-scale values of Reynolds number. Because of the urgent need for a reasonable size transonic tunnel capable of testing at or near full-scale Reynolds number, the work on magnetic-suspension and balance systems was temporarily set aside as a small team of researchers was established to solve any practical problems that might be found in trying to make the cryogenic wind tunnel concept work.

The chart shown above contains two excerpts from Dr. Goodyer's NASA - Langley "Laboratory Notebook".¹²

Cryogenic Tunnel Concept

- $R = \frac{\text{inertia force}}{\text{viscous force}} = \frac{\rho V l^2}{\mu V l} = \frac{\rho V l}{\mu} = \frac{\rho M a l}{\mu}$
- Model loads $\propto q = \frac{\rho V^2}{2} = \frac{\rho M^2 a^2}{2}$
- Tunnel power $\propto qV = qMa$

For constant model and tunnel size, pressure, and Mach number:



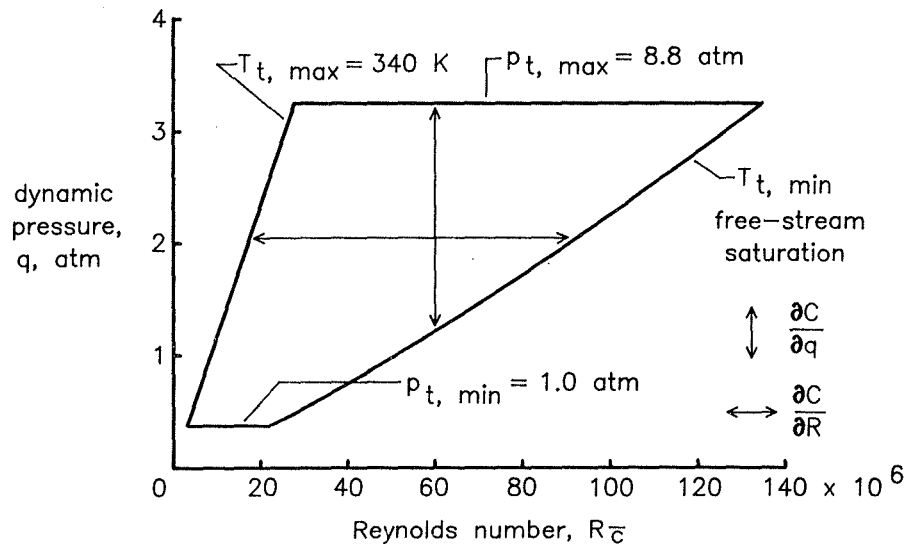
The effects of a reduction in temperature on the gas properties, test conditions, and drive power are illustrated on this chart.

For comparison purposes, a stagnation temperature of 322 K (49°C) for normal ambient temperature tunnels is assumed as a datum. The variation in gas properties with temperature is shown on the left for conditions of constant pressure and the approximate temperature dependence is shown with each curve. The corresponding variation in test conditions and drive power are shown on the right for conditions of constant model and tunnel size, constant pressure, and constant Mach number.

It can be seen that cooling the test gas sufficiently results in an increase in Reynolds number by more than a factor of 7 with no increase in dynamic pressure and with a large reduction in the required drive power. To obtain such an increase in Reynolds number without increasing either the tunnel size or the operating pressure while actually reducing the drive power is extremely attractive and makes the cryogenic approach to a high Reynolds number transonic tunnel much more desirable than previous approaches.

Constant Mach Number Operating Envelope

$M_\infty = 1.0$, 2.5 x 2.5 m test section



The high Reynolds number capability at reasonable model loads and the reduced capital and operating costs are not the only advantages of a cryogenic wind tunnel. Very important additional advantages are offered due to the fact that a cryogenic tunnel with the independent control of Mach number, temperature, and pressure has the unique capability to determine independently the effect of Mach number, Reynolds number, and aeroelastic distortion on the aerodynamic characteristics of the model. This new and unique aerodynamic testing capability may be, in some instances, of equal importance with the ability to achieve full-scale Reynolds number.

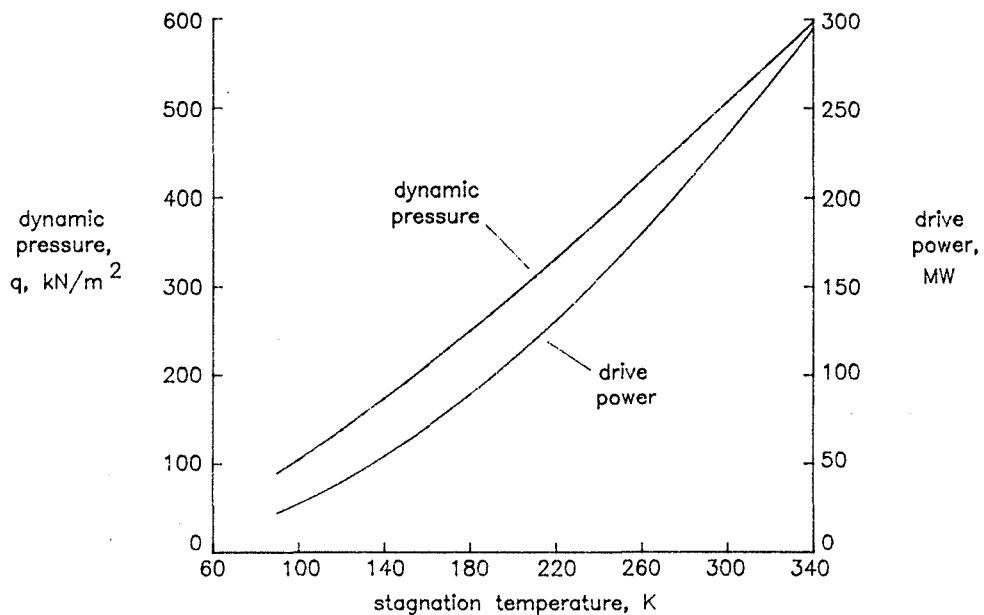
In order to illustrate these additional research advantages, a typical constant Mach number operating envelope is shown on this chart for a tunnel having a 2.5 x 2.5 m test section. The envelope shows the range of dynamic pressure and Reynolds number available for sonic testing. It is bounded by the maximum temperature boundary (340 K), the minimum temperature boundary (chosen to avoid saturation at free-stream conditions), the maximum pressure boundary (8.8 atm), and the minimum pressure boundary (1.0 atm). Since conventional, ambient-temperature pressure tunnels permit only minor temperature control -- being essentially limited to operation along the ambient-temperature line -- they encounter large changes in dynamic pressure, and therefore, large changes in model deformation, with changes in Reynolds number.

In contrast, with the cryogenic tunnel, with its large constant-Mach-number operating envelope, it is possible, for example, to determine at a constant Mach number the true effect of Reynolds number on the aerodynamic characteristics of the model without having the results influenced by changing model shape due to changing dynamic pressure. (There

will be a slight variation of the modulus of elasticity E of most model materials with temperature. To correct for this variation in E , the dynamic pressure Q may be adjusted by varying total pressure so that the ratio q/E remains constant over the Reynolds number range.) This ability to make pure Reynolds number studies is of particular importance, for example, in research on the effects of the interaction between the shock and the boundary layer. As indicated on the envelope, pure aeroelastic studies may be made under conditions of constant Reynolds number. In addition, combinations of R and q can be established to represent accurately the variations in flight of aeroelastic deformation and changes in Reynolds number with altitude. Similar envelopes are, of course, available for other Mach numbers.

Effect of Temperature on Dynamic Pressure and Drive Power

$M_{\infty} = 1.0$, $R_{\tau} = 50 \times 10^6$, 2.5 x 2.5 m test section



UTSI-5 DAD 4-21-82

For a selected tunnel size and Reynolds number, the previously described effects of cryogenic operation are manifested in large reductions in the required tunnel stagnation pressure and therefore in large reductions in both the dynamic pressure and the drive power. These reductions are illustrated on this chart, where both dynamic pressure and drive power are shown as functions of stagnation temperature for a constant chord Reynolds number of 50 million at a free-stream Mach number of 1.0 for a tunnel having a 2.5 x 2.5 m test section. As the tunnel operating temperature is reduced, the large reductions in both dynamic pressure and drive power provide the desired relief from the extremely high values that would be required for a pressure tunnel operating at normal temperatures.

The large reduction in drive power makes a fan-driven tunnel practical even at this relatively high Reynolds number. The resulting efficiency and increased run time provide, in general, several important advantages relative to intermittent tunnels, such as increased productivity, improved dynamic testing capability, and, as can be shown, reduced total energy consumption (and therefore operating costs) for equal amounts of testing.

A Cryogenic Tunnel offers the unique ability to –

- * Achieve full-scale Reynolds number with reasonable –
 - Model and tunnel size
 - Dynamic pressure
 - Drive power

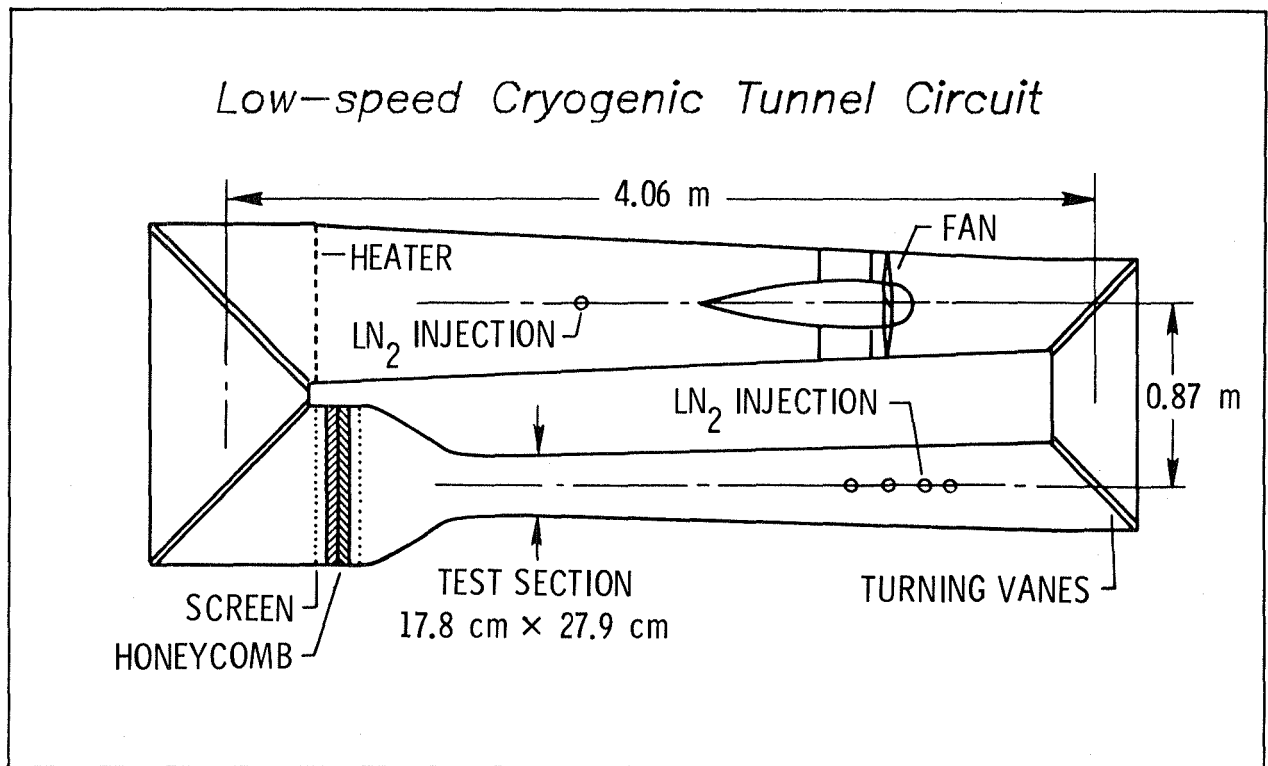
- * Separate effects of –
 - Reynolds number
 - Mach number
 - Aeroelasticity

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This chart is intended to reiterate the major advantages of cryogenic tunnels.

In contrast with all other approaches to increasing test Reynolds number, the cryogenic approach makes it possible to achieve full-scale values of Reynolds number in a tunnel of reasonable size at reasonable levels of dynamic pressure and drive power.

In addition, the unique tunnel operating modes, made possible by having test temperature as an independent variable, make possible for the first time the separation of the aerodynamic effects due to Reynolds number, Mach number, and aeroelasticity.

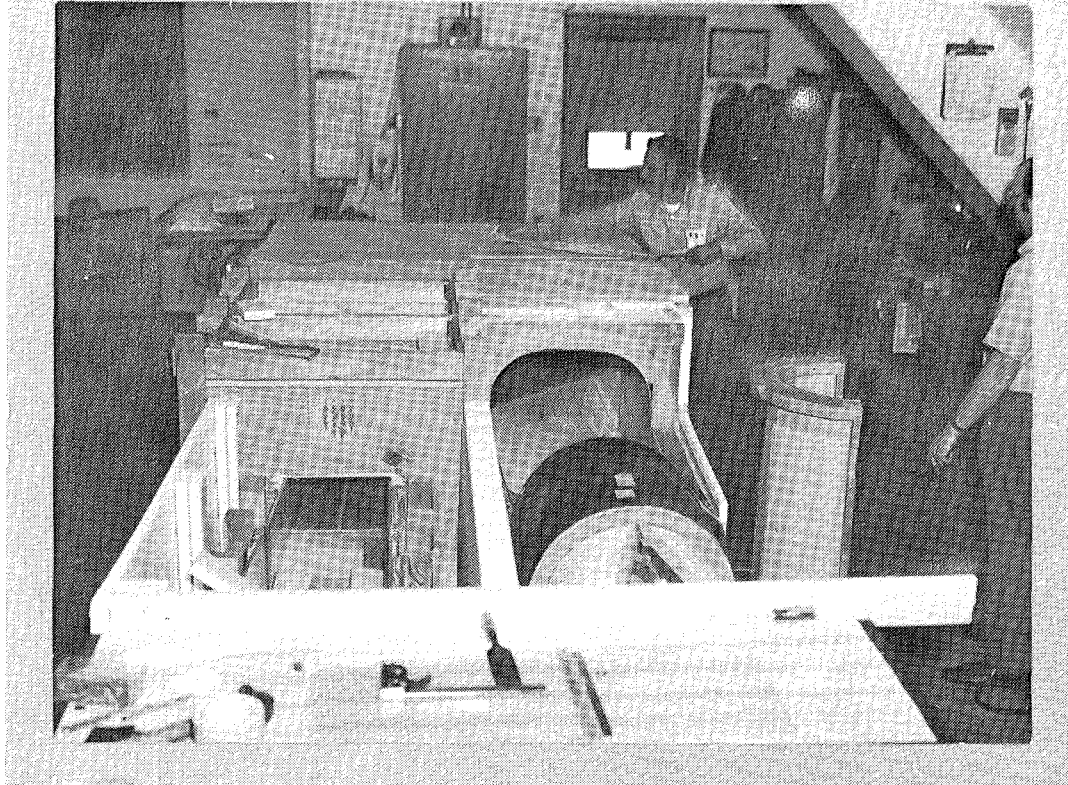


By January of 1972, the cryogenic wind tunnel concept had been turned into hardware with the successful operation of an atmospheric low-speed cryogenic tunnel at Langley. This tunnel was used for a variety of so-called "proof-of-concept" tests thru the spring and summer of 1972. A sketch of the low-speed tunnel is shown above.

The tunnel was cooled and the heat of compression added to the stream by the fan was removed by spraying liquid nitrogen at about 78 K directly into the tunnel circuit in either of the two locations shown in the sketch.

The rate of cooling was such that, for example, a temperature of 116 K could be stabilized within 10 minutes of the initiation of cooling from room temperature. The tunnel was operated at temperatures from 333 K to 80 K. The lower temperature is very close to the saturation temperature of nitrogen of 77.4 K at 1 atmosphere. Approximately 40 hours of tunnel operation was at cryogenic temperatures, that is, below 150 K. At the reference station in the test section the test temperature was held to within about ± 1 K by automatic on-off control of one or more of the liquid nitrogen injection nozzles. Much closer temperature control was achieved by injecting a slight excess amount of liquid nitrogen and establishing temperature equilibrium at the desired test temperature by modulating the heat input from a simple wire-grid electric heater built into the tunnel. Using this technique, test temperatures could be held to within about ± 0.2 K.

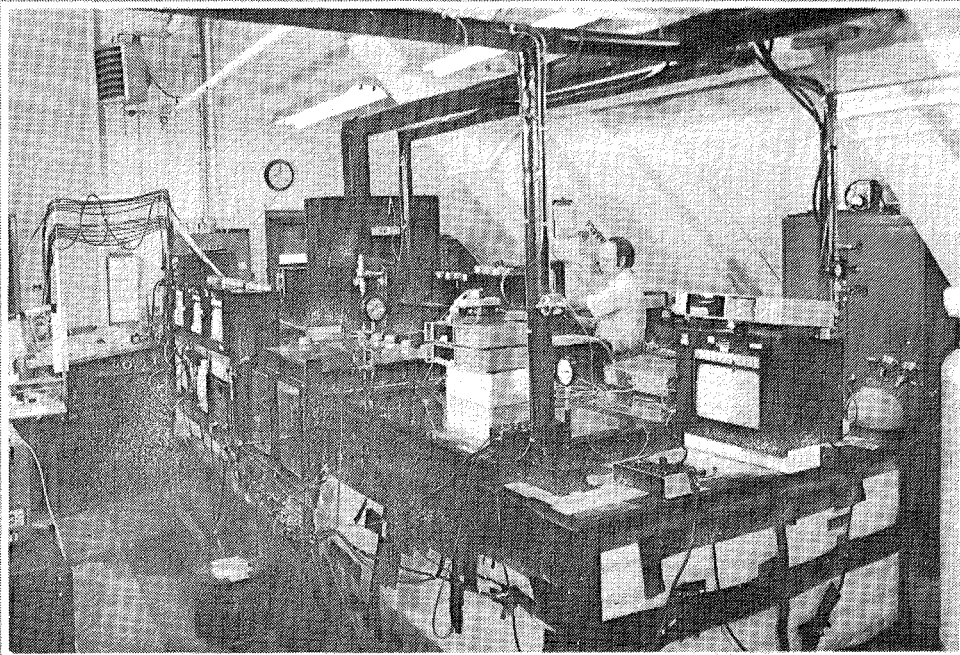
INSULATION OF LOW-SPEED CRYOGENIC TUNNEL



A photograph of the low-speed tunnel being insulated is shown above. Since the basic tunnel circuit was already built, the low-speed tunnel project was a very low-budget research effort. The cost of materials used to modify and insulate the tunnel circuit was less than \$2000 (1971-1972). Materials of construction included wood, plywood, plexiglas, mild and stainless steels, aluminum, brass, copper, and fiberglass reinforced plastic. The fan blades were made of laminated wood.

Viewing ports were provided to allow inspection of key areas of the tunnel circuit including the test section, spray zones, corner vanes, screen section, and contraction section. The viewing ports consisted of either 3 or 4 layers of plexiglas separated by air gaps. Thermal insulation for the remainder of the tunnel circuit was a 7.6 to 10.2 cm (3" to 4") layer of expanded styrofoam applied to the outside of the tunnel with a 0.0127 cm (0.005") thick polyethylene vapor barrier on the outside.

LOW-SPEED CRYOGENIC TUNNEL



A photograph of the fully insulated low-speed tunnel is shown above. Most of the instrumentation seen sitting on the tunnel was used to measure the liquid nitrogen flow rate and to determine the temperature distribution around the tunnel, since in the early stages of the project, the main concern was finding an efficient yet simple way to cool the tunnel and still have temperature uniformity, in both time and space, within the test section.

Once adequate operating procedures were worked out, the low-speed tunnel was used to experimentally verify, insofar as possible, the validity and practicality of the cryogenic concept.

Low-Speed Cryogenic Tunnel Results

Aerodynamic

- * Boundary-layer development with R found to be identical for ambient and cryogenic conditions.
- * Drive-power and fan-speed found to decrease as predicted.

Operational

- * Cooling with LN_2 is practical.
 - Rapid cooldown
 - Automatic temperature control
 - Gas stream is clear, dry, and frost free
- * Use of conventional strain-gage balance is practical.
- * Trouble-free operation of drive motor and fan.

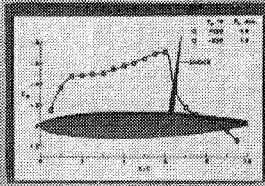
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Two simple "proof-of-concept" experiments were made in the low-speed cryogenic tunnel. One, using a flat plate with a laminar boundary layer, demonstrated that the true aerodynamic effects of Reynolds number increases are indeed provided when temperatures are reduced to the cryogenic range. The second, using a sharp leading edge delta wing model, verified that conventional strain-gage balance techniques might be used to make force and moment measurements at cryogenic temperatures.

In addition to the two "proof-of-concept" experiments, other experiments, mainly related to developing acceptable cooling techniques and operating procedures, were made in the low-speed tunnel. The main conclusions, both aerodynamic and operational, drawn from the experiments as well as from the day-to-day operation of the low-speed cryogenic tunnel, are outlined on this chart.

0.3-METER TRANSONIC CRYOGENIC TUNNEL

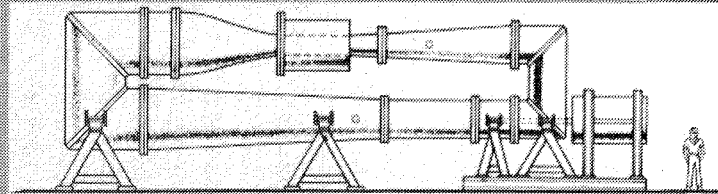
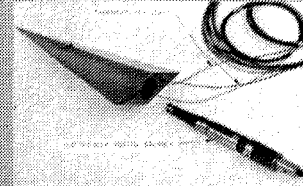
VALIDATION TESTS



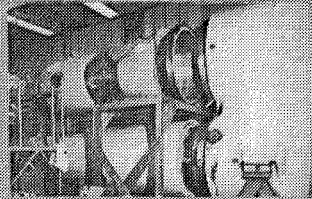
OPERATIONAL EXPERIENCE



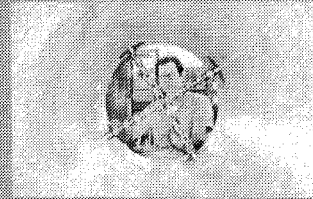
INSTRUMENTATION DEVELOPMENT



CRYOGENIC SHELL CONSTRUCTION



COOLING TECHNIQUES



Following the successful completion of the low-speed tunnel work in the summer of 1972, the decision was made to build a relatively small fan-driven transonic cryogenic pressure tunnel in order to extend our experience with cryogenic tunnels to the pressure and speed range contemplated for a large high Reynolds number transonic cryogenic tunnel.

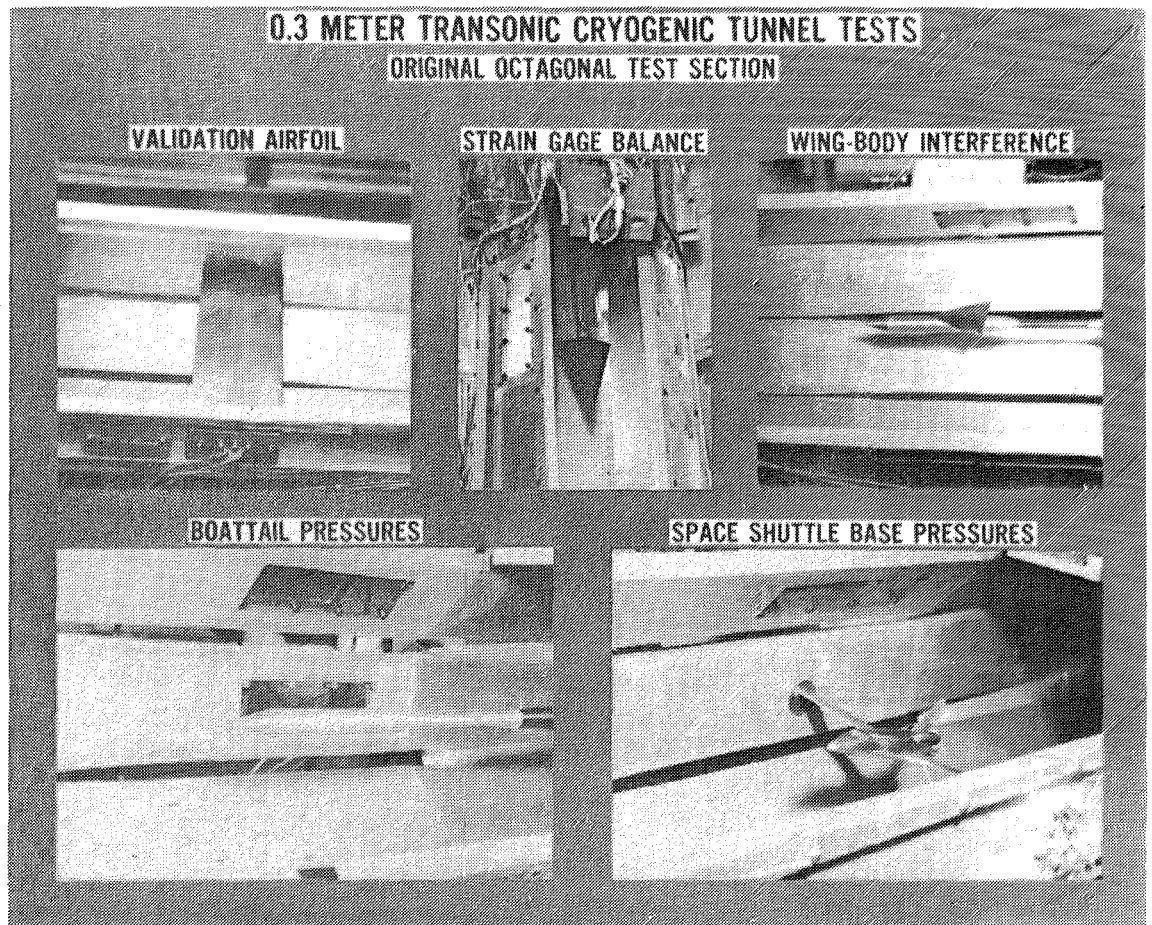
Design of the "pilot" transonic cryogenic tunnel began in December of 1972 and initial operation began in August of 1973. The first run at cryogenic temperatures (150 K or lower) was made on October 16, 1973, less than two years after work was started on the cryogenic tunnel concept.

The above figure shows a sketch of the pilot tunnel surrounded by photographs illustrating some of the uses to which it has been put since 1973.

The pilot transonic cryogenic tunnel, which originally had a 34 cm octagonal test section, was successfully used to verify the cryogenic wind tunnel concept at transonic speeds and provided much needed design and operational experience for the development of larger cryogenic transonic tunnels.

The most significant test, illustrated in the upper left of the figure, was of a so-called "validation airfoil". Based on the "real-gas" studies of Adcock, there was little doubt that airfoil pressure distributions measured for given values of Reynolds number and Mach number should be the same at cryogenic and ambient temperature conditions. However, in order to provide experimental verification of this equivalence, the pressure distribution on a two-dimensional airfoil was measured in the pilot tunnel at ambient and cryogenic temperatures under conditions of constant Reynolds number and Mach number. The nearly perfect agreement in the pressure distributions, as shown in the figure, provided the first

experimental confirmation at transonic speeds that nitrogen at cryogenic temperatures behaves like a perfect gas and is therefore a valid transonic test gas as predicted by the real gas studies.



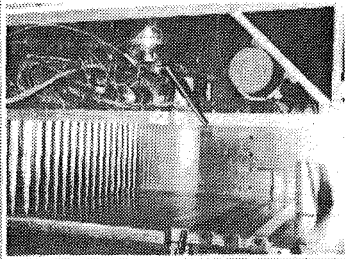
The above figure shows photographs of several of the models tested in the original octagonal test section of the pilot transonic tunnel, including the "validation airfoil" previously discussed.

Some of the models, such as the delta-wing model with an internal strain-gage balance, were extensions of earlier work in the low-speed cryogenic tunnel and were part of a general program undertaken at Langley to develop instrumentation. Models such as The Boattail Pressure Model, the Space Shuttle Orbiter Model, and the Wing-body Interference Model, were among those tested in the pilot transonic tunnel in order to determine their aerodynamic characteristics, either taking advantage of the relatively high maximum Reynolds number capability or taking advantage of the extremely wide range of Reynolds number available in the pilot transonic cryogenic tunnel.

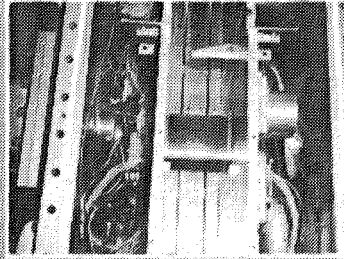
0.3m TRANSONIC CRYOGENIC TUNNEL TESTS

20 BY 60cm 2-D TEST SECTION

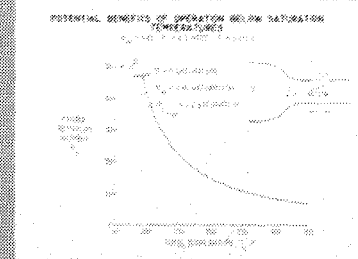
NTF COOLING COIL



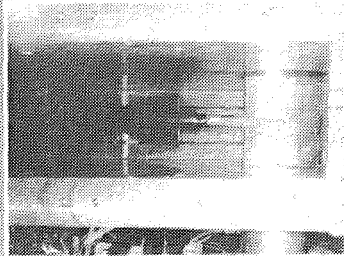
AIRFOIL RESEARCH



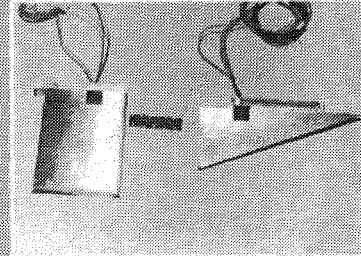
CONDENSATION LIMITS



SECOND GENERATION BALANCE TESTS



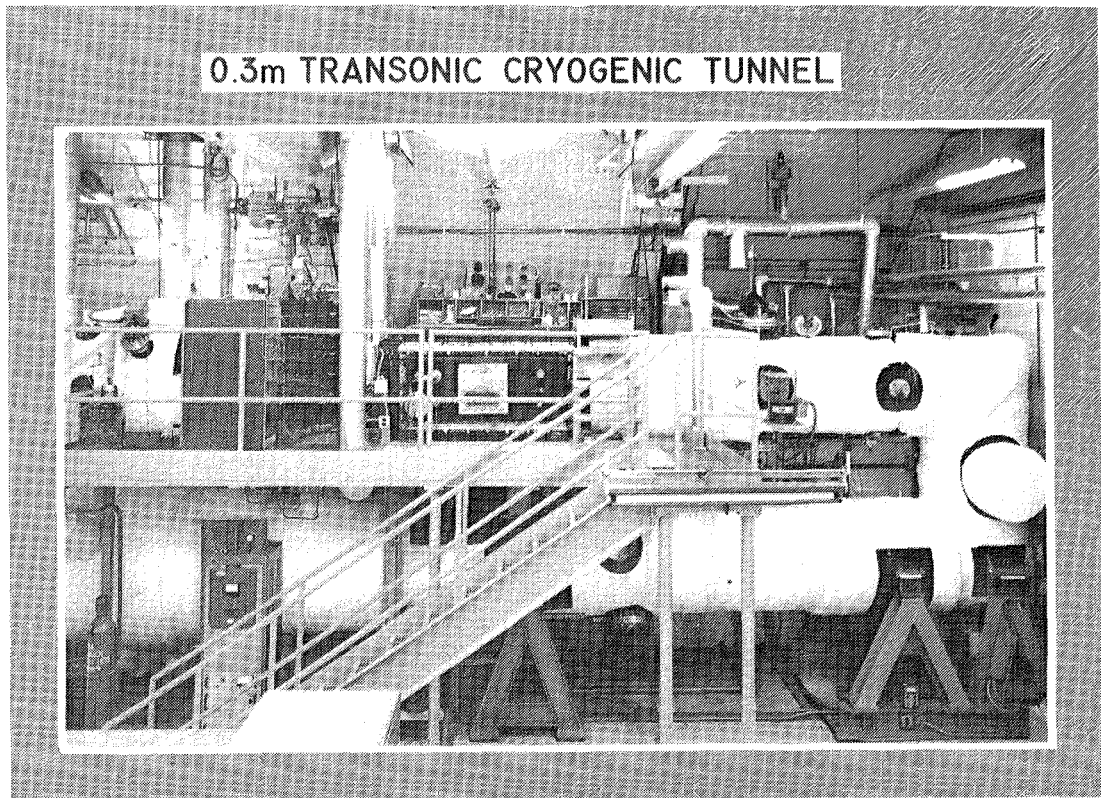
DEVELOP BUFFET TECHNIQUE



In the summer of 1976, the pilot transonic cryogenic tunnel was fitted with an 8" x 24" 2-dimensional test section, classified as a NASA "facility" and re-named the 0.3-m Transonic Cryogenic Tunnel, commonly referred to as the 0.3-m TCT.

The operating pressure of the 0.3-m TCT has recently been increased to slightly over 6 atmospheres, making it the highest Reynolds number airfoil testing facility in the world. In addition to testing advanced airfoils, the 0.3-m TCT is being used to support a program at Langley aimed at developing cryogenic tunnel technology in areas such as model construction, test techniques, control systems, and efficient operating procedures.

The sketch and photographs of the above figure illustrate a few of the research programs that have been done in the 0.3-m TCT since the 2-dimensional test section was placed in operation in 1976.



The above photograph gives a fairly recent view of the 0.3-m TCT fitted with the 33 x 33 cm adaptive wall test section.

The tunnel circuit is in the vertical plane with the test section at the top. Flow is clockwise with liquid nitrogen injection through four digital valves downstream of the test section and gaseous nitrogen exhaust through control valves from the "big end" at the left in the photograph. The vertical pipes just upstream of the test section allow both plenum and test section sidewall boundary-layer removal through two digital control valves mounted on the roof of the building.

Two other features that are unique to cryogenic tunnels are also shown in the photograph. The first is the thermal insulation system, which for the 0.3-m TCT is outside the aluminum pressure shell. The second feature is the Teflon pads fitted between the A-frame supports and the tunnel pressure shell. These pads provide both insulation and low friction surfaces to accommodate the considerable contraction and expansion of the pressure shell as the tunnel is cycled over its extremely wide temperature range.

Capabilities of 0.3-m TCT

Continuous running

33 x 33 cm adaptive wall test section

p_t 1.1 to 6.12 atm

T_t 77.4 to 340 K

M 0.02 to 1.3 ?

R/m 0.4 to 400 million

-500 to 1 range for incompressible flow

-25 to 1 range for compressible flow

R_c to 60 million for $c = 15$ cm

TCT (5) 9/85

This chart lists some of the operating characteristics and testing capabilities of the 0.3-m TCT.

From the aerodynamic research point of view, the most significant capabilities are the high unit Reynolds number, up to 400 million per meter, and the very wide range of Reynolds number that can be achieved by taking full advantage of the wide ranges of operating temperature and pressure.

Present Uses of 0.3-m TCT

- * High Reynolds number airfoil research.
- * Development of technology required for the efficient use of cryogenic wind tunnels.

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In addition to testing advanced airfoils, the 0.3-m TCT is being used to support a program at Langley aimed at developing cryogenic tunnel technology in areas such as model construction, test techniques, control systems, and efficient operating procedures.

National Transonic Facility AACB Recommendations

* A single transonic test facility identified as the National Transonic Facility (NTF)

* *Cryogenic concept*

* Characteristics:

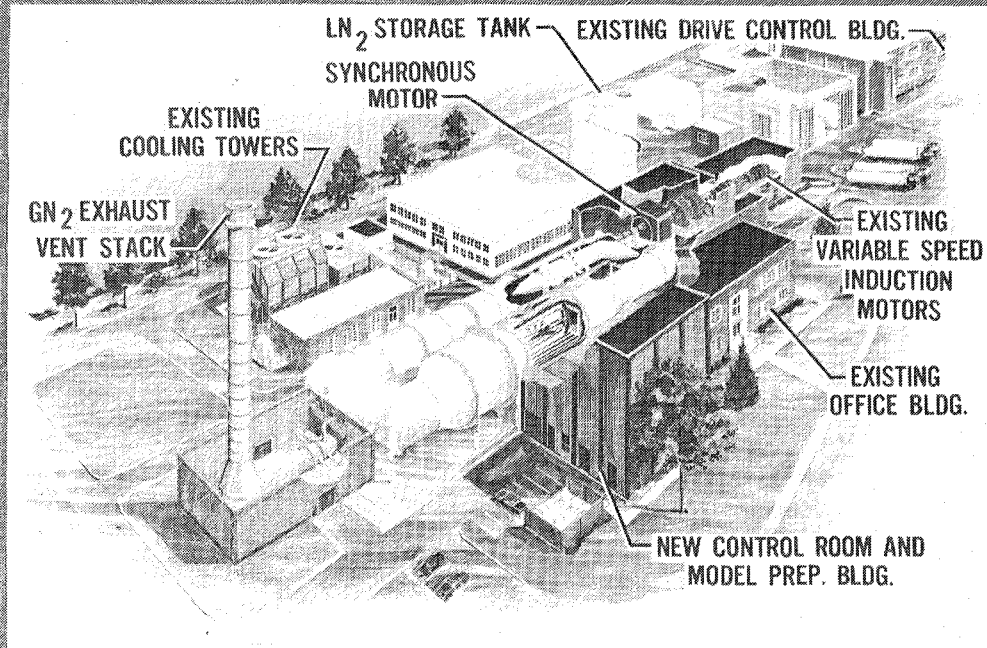
Test section size	2.5 x 2.5 m
Design pressure	8.8 atm
Design Mach number range	0.2 - 1.2
Stream fluid	Nitrogen
Basic drive power	90 megawatts
Productivity/efficiency	8000 polars/year
Reynolds number	120 million ($M_{\infty} = 1.0$)

* Located at *Langley Research Center*

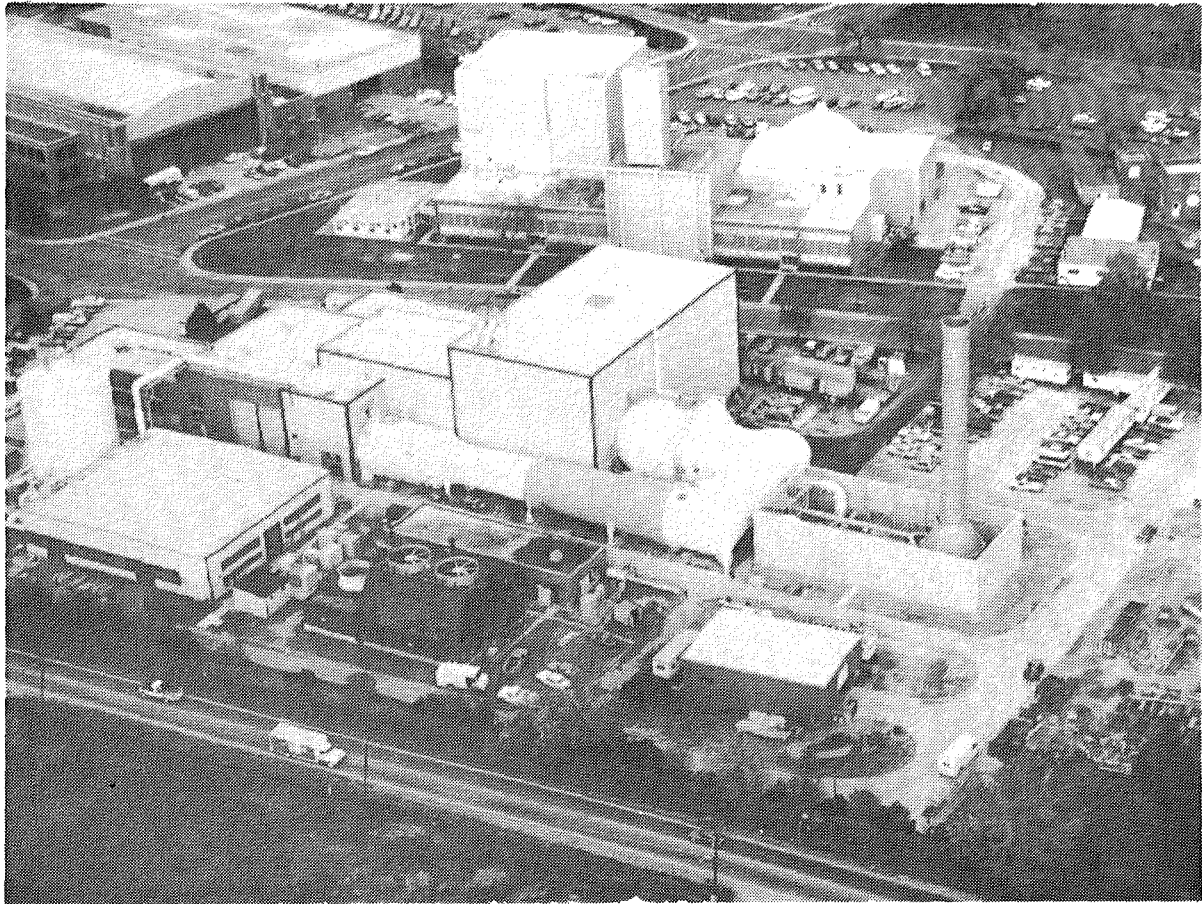
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As previously mentioned, along with the early experimental work on cryogenic tunnels, there was a parallel theoretical study by Adcock of the so-called "real gas effects" resulting from operating a transonic tunnel using nitrogen gas at cryogenic temperatures. Adcock's studies, combined with the experimental verification of the cryogenic tunnel concept at transonic speeds in the 0.3-m TCT, had a far reaching effect. Several proposed ambient temperature high Reynolds number intermittent tunnels, both in the U. S. and in Europe, were abandoned as the superiority of the cryogenic concept became more widely recognized. A direct and most significant outcome of this work was the decision in 1975 by the joint Air Force/NASA Aeronautics and Astronautics Coordinating Board (AACB) to build a single large transonic cryogenic tunnel to meet the high Reynolds number testing needs of the United States. The AACB recommendations relative to the proposed National Transonic Facility (NTF) are shown on the above chart. Implementation of the AACB decision is evidenced by the construction of the NTF at the NASA Langley Research Center in Hampton, Virginia.

NATIONAL TRANSONIC FACILITY PERSPECTIVE



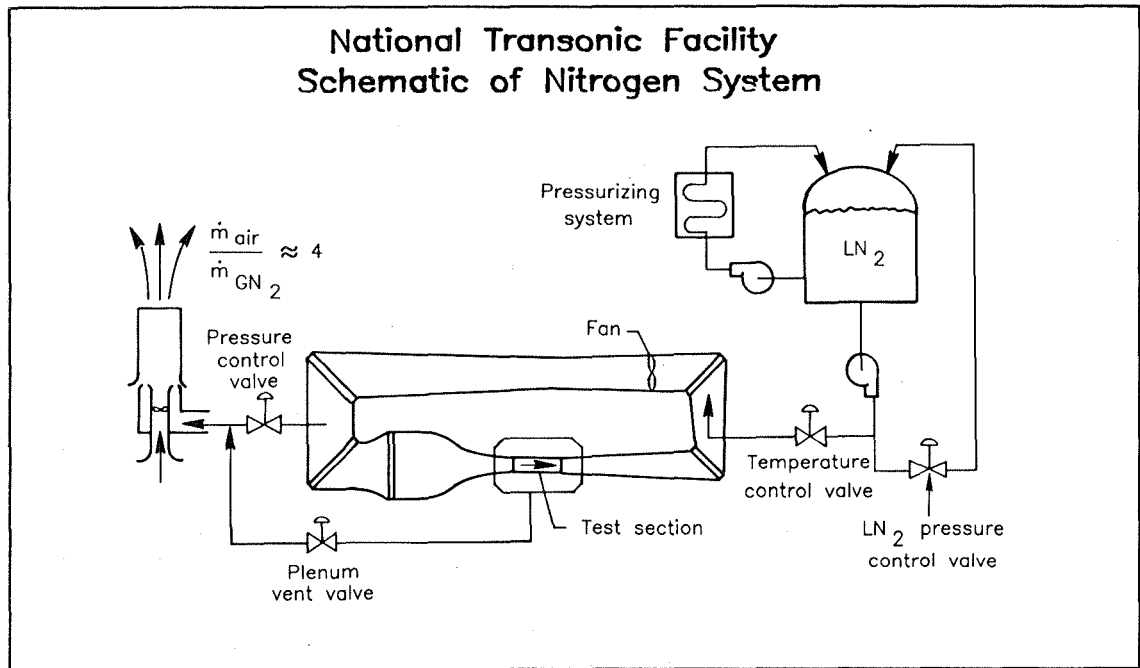
Shown above is an artist's sketch of the NTF showing most of the main design features. The site of the NTF is that of a former 4' supersonic tunnel at Langley making it possible to reduce construction costs by using an existing drive system and office building.



Before going into any details on the design or capabilities of the NTF, we want to show an aerial view of the NTF site. This is done to point out very graphically the fact that there is a considerable difference in scale and complexity between the NTF and the first low-speed cryogenic tunnel built at Langley just over thirteen years ago.

On the left can be seen the 946 cubic meter capacity liquid nitrogen storage tank and at the right the 37 m high gaseous nitrogen exhaust stack. Liquid nitrogen is supplied to the storage tank through a pipeline connected to a 302 ton/day liquid nitrogen plant built by Union Carbide on commercial property near the tunnel site or, if necessary, through a truck off-loading station near the NTF storage tank.

National Transonic Facility Schematic of Nitrogen System



Essential to the operation of the NTF is the ability to inject large amounts of liquid nitrogen into the tunnel, achieve reasonably uniform mixing and evaporation, and exhaust equally large amounts of gaseous nitrogen. The sketch above shows, in very simplified schematic form, the liquid nitrogen supply system and the gaseous nitrogen exhaust system.

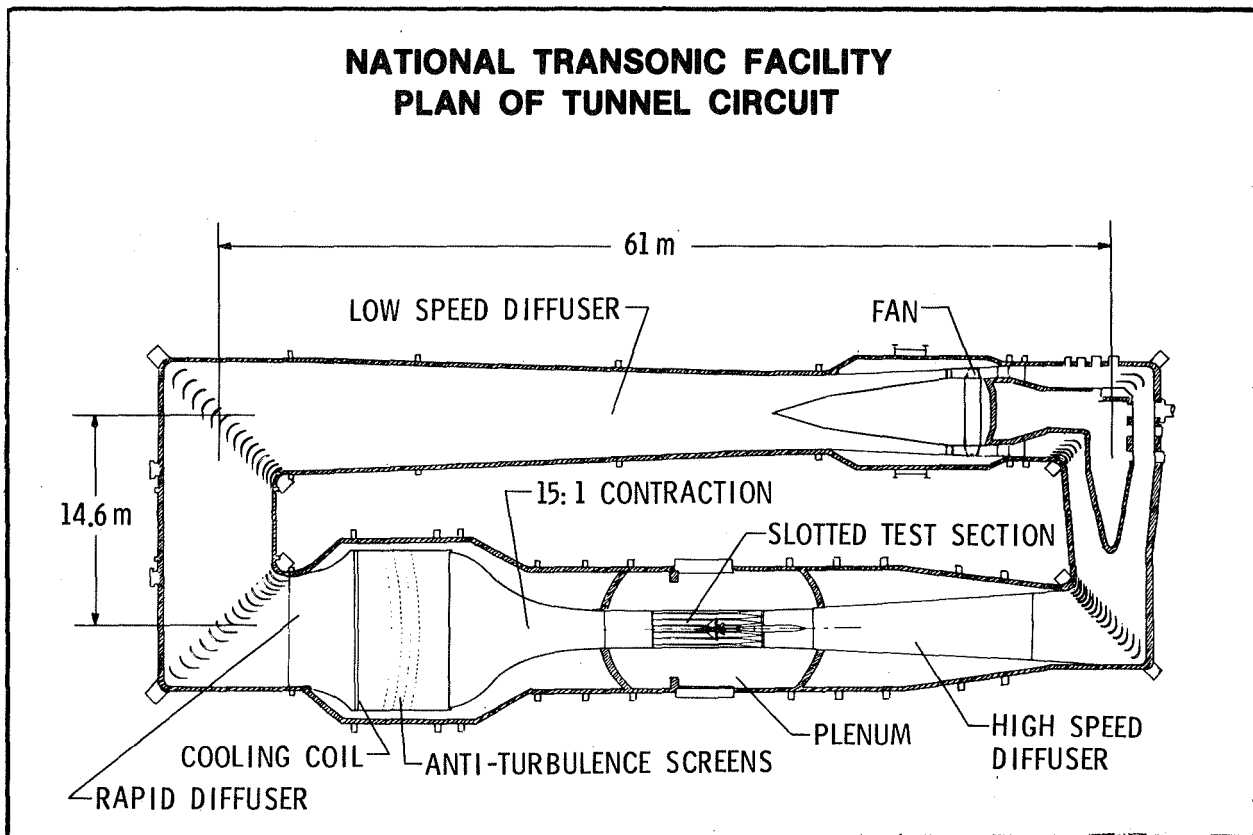
The liquid nitrogen supply system consists of the storage tank, pumps, and appropriate valves. A vaporizer is used to keep the ullage in the supply tank at atmospheric pressure while liquid is being removed. The liquid nitrogen is sprayed into the tunnel circuit upstream of the fan.

The maximum mass flow through the system is approximately 454 kg/sec (1000 lbs per sec). In the design, three pumps are used instead of a single large one for reasons of cost and efficiency. The smallest pump is used for tunnel cooldown. The other two are either used separately or together depending on flow rate requirements.

The tunnel pressure is controlled by valves at the large end of the tunnel. Where constant operating temperature and pressure are required, the mass flow vented is equal to the liquid mass flow injected and is directly proportional to the energy added to the stream by the fan and the heat that leaks into the circuit through the insulation.

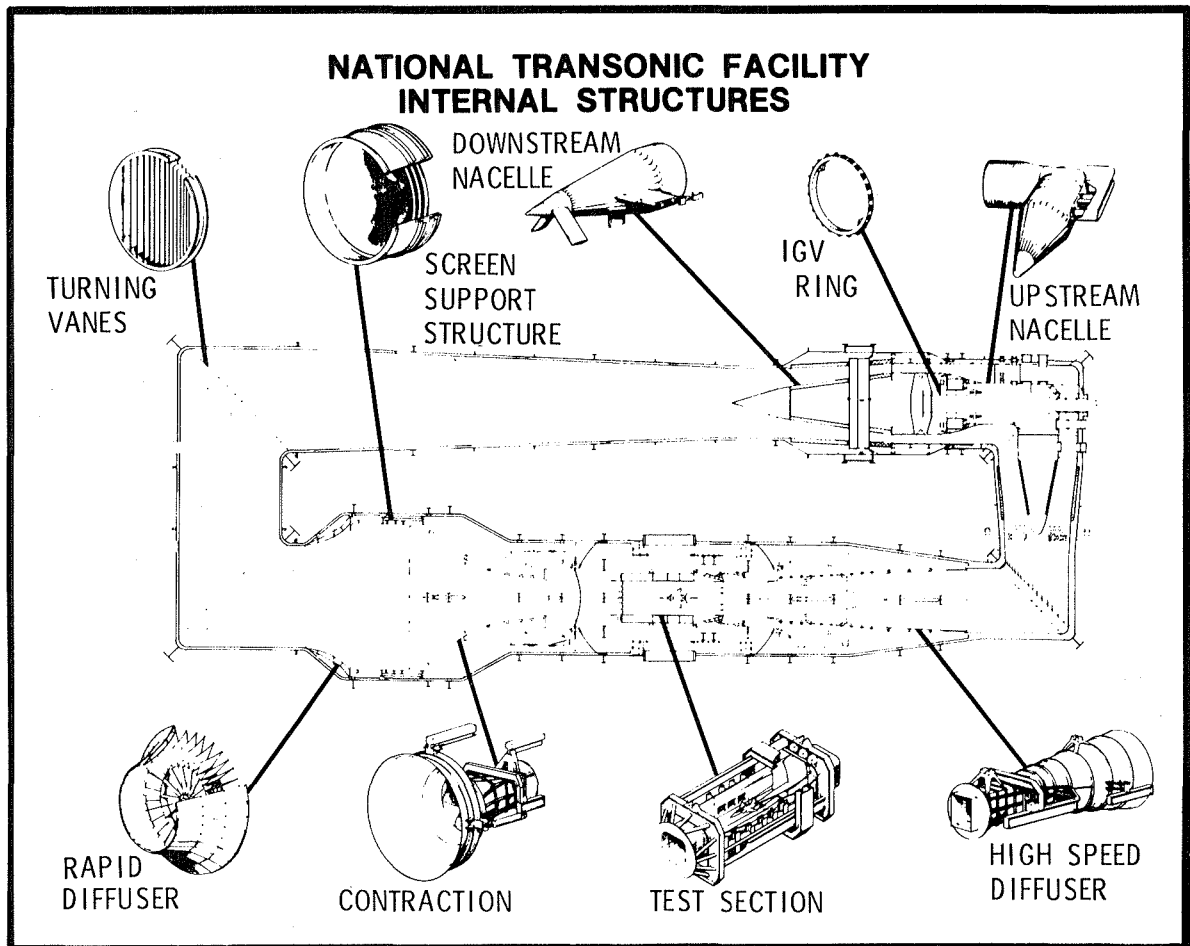
The vent system discharges from the tunnel through two control valves into a muffler which attenuates valve noise and exhausts into the base of a 37 meter (120 ft) high vent stack. The momentum of the discharge from the tunnel is used to induce air into the base of the stack. The system is designed to assure that the mixture of air and nitrogen at the discharge of the stack has sufficient oxygen to sustain life. The minimum upward velocity at discharge is designed to be about 21 m/sec (70 ft/sec) which should assure adequate mixing with surrounding air so that no thermal problem will occur if the plume returns to ground level. For low pressure operation of the tunnel, four axial flow fans pump air up the stack and provide the required momentum at the discharge.

NATIONAL TRANSONIC FACILITY PLAN OF TUNNEL CIRCUIT



The aerodynamic lines of the NTF are shown above. The centerline dimensions are 61 m in the long direction and 14.6 m in the short direction. Although the high Reynolds number mode of operation requires the use of cryogenic temperatures, and therefore the use of nitrogen as the test gas, low Reynolds number tests can be made using air with the heat of compression of the fan being removed by a water cooled heat exchanger.

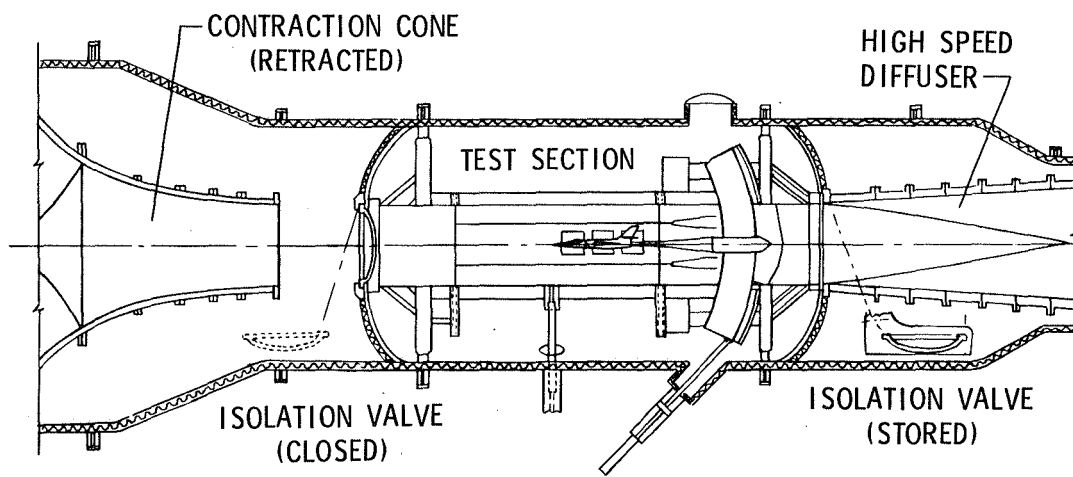
In keeping with AACB recommendations, the NTF has a 2.5 x 2.5 m test section and is designed to operate at Mach numbers from 0.2 to 1.2 at pressures from about 1 to 8.8 atmospheres. Although the AACB only recommended that the NTF use the "cryogenic concept", the tunnel does, in fact, operate at temperatures from 350 to 77 kelvin. At maximum pressure and minimum temperature, this will give a test Reynolds number of at least 120 million at Mach 1 based on a reference length of 0.25 m.



The above figure shows more detail of the major internal components of the NTF.

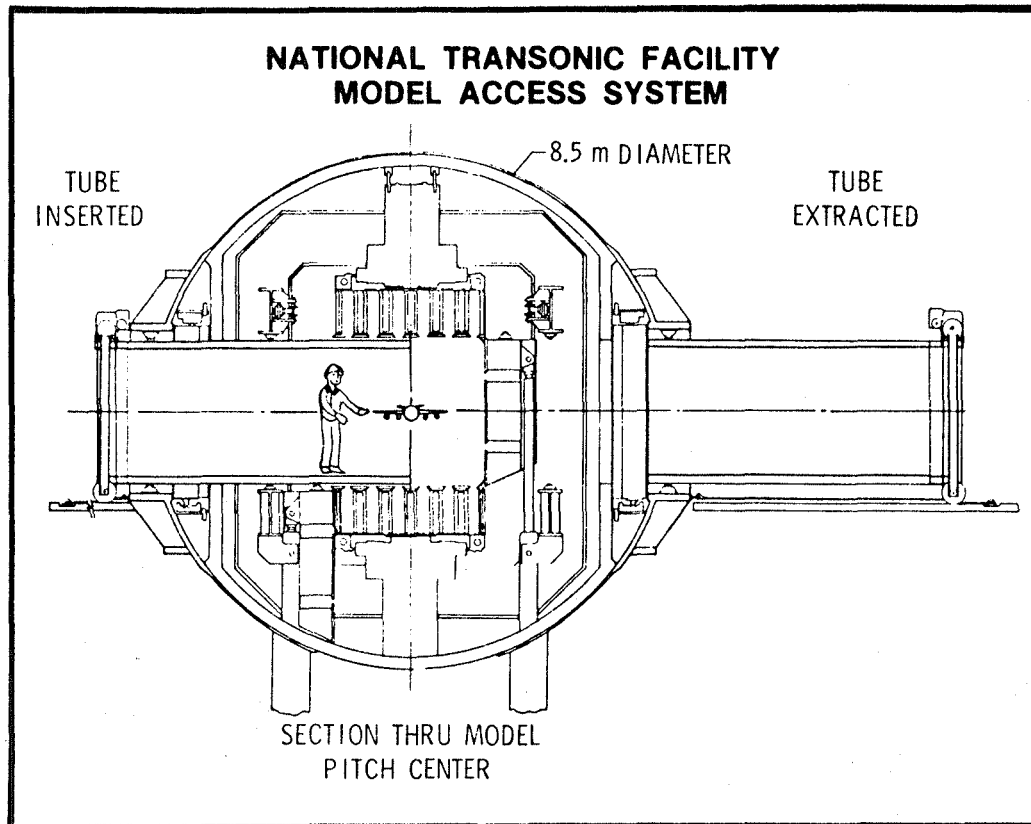
The NTF is a rather conventional transonic wind tunnel with only a few unconventional features, related for the most part to the cryogenic mode of operation. Examples of such features are injection nozzles, located near the beginning of the upstream nacelle, capable of spraying liquid nitrogen into the tunnel at rates up to 450 kg per second, a gaseous nitrogen exhaust stack, internal thermal insulation, test section isolation valves, and a pressure shell constructed of approximately 5.5 million pounds of 304 stainless steel. In addition, there is a million pounds or so of material, mostly aluminum alloy, in the internal components which are exposed to the stream and therefore undergo large temperature changes when the tunnel is cycled between ambient and cryogenic conditions. The design and construction of the NTF has brought together for the first time the technology of large transonic wind tunnels and modern cryogenic engineering.

NATIONAL TRANSONIC FACILITY TEST PLENUM ISOLATION SYSTEM



Early in the design of the NTF, it became obvious that even though the cryogenic approach was the most cost effective of all approaches considered, high Reynolds number tests would be more expensive than conventional low Reynolds number wind tunnel tests, and we would need to take advantage of every opportunity to reduce operating cost. One cost effective system included in the design of the NTF is a system for test section plenum isolation, shown above, which permits changes to be made to the model while the remainder of the tunnel circuit is pressurized with cold nitrogen gas.

To achieve test section isolation, the contraction section and high speed diffuser are uncoupled and moved away from the plenum bulkheads on a sliding pad-rail system. The isolation valves are raised, positioned, and dogged to each bulkhead opening in order to isolate the plenum volume from the rest of the circuit. The plenum volume is then vented to the atmosphere and the model access system activated.



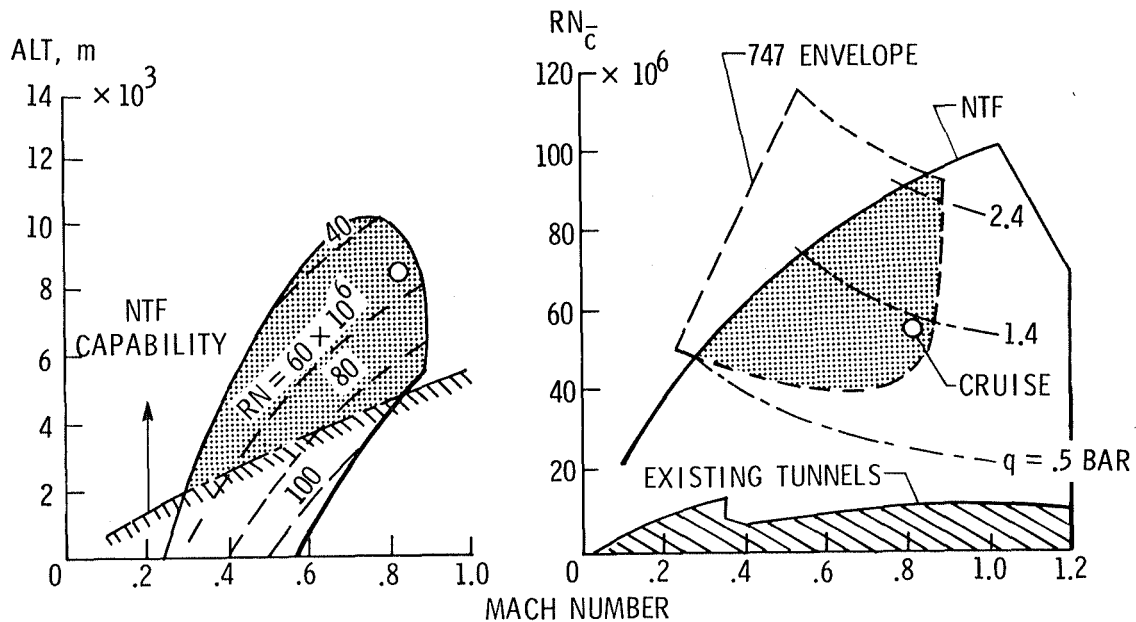
The figure above shows the NTF model access system. It consists of two tubes having rectangular cross sections and doors at the outer ends. The tubes are mounted in the opening of large (2.74 x 3.66 m) doors, giving access to the plenum and test section. These doors can be unseated and moved on internal tracks to their open position. The side walls of the test section are lowered and the two access tubes inserted. Then the two tubes meet in the center of the test section, they surround the model in the tube and seal around the model support sting. The tube volume is then purged with air to provide a working environment and the end doors are open to allow a through passage. Provisions are also made to heat the model as required. To go back into operation, the process is reversed.

Additional Sources of Information

There are many more details of the NTF design that could be discussed. However, much of the information that might be of interest is available as NASA CP-2122, the printed version of a conference on Cryogenic Technology held at NASA-Langley in November of 1979 (Ref. 24).

An additional source of information is a paper entitled "Status of the National Transonic Facility" by McKinney and Gloss (Ref. 25), which goes into detail on the NTF model and instrumentation activities as well as the calibration plans and the initial research program.

NATIONAL TRANSONIC FACILITY COMPARISON OF TEST AND FLIGHT ENVELOPES (B-747)

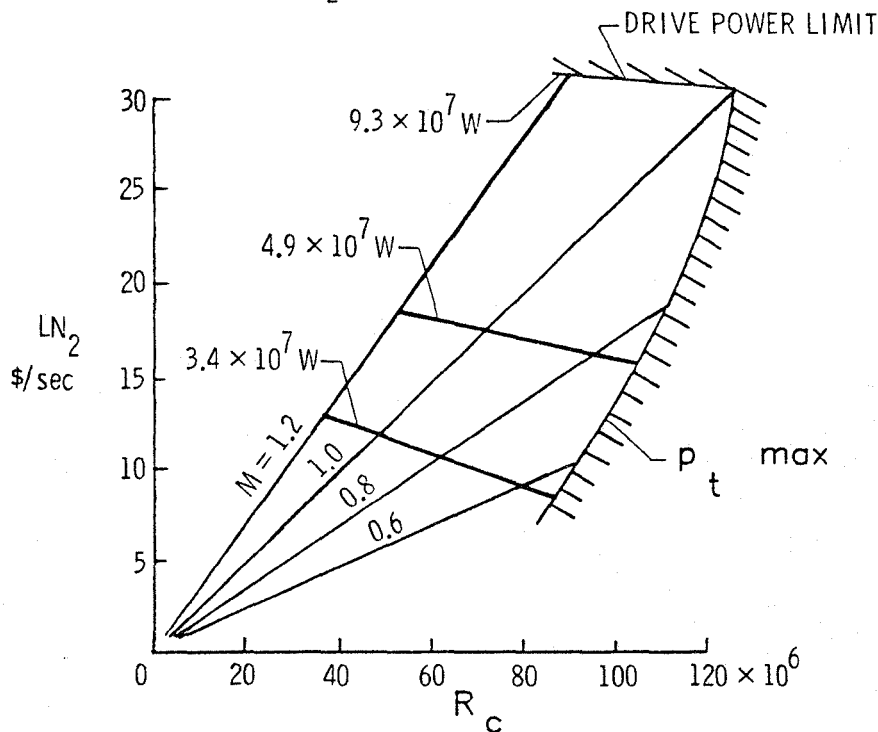


The ability of the NTF to test at full scale Reynolds number is illustrated above, where flight at full scale and test at model scale in the NTF are compared.* The airplane used in this comparison is the well known Boeing 747. On the left is a plot of the airplane flight envelope in terms of altitude as a function of Mach number. Lines of constant Reynolds number are shown within the flight envelope. On the right, the flight envelope has been superimposed on the NTF test envelope which is presented in terms of Reynolds number and Mach number for a properly sized model. The part of the flight envelope covered by the NTF test envelope is where full scale flight Reynolds numbers can be achieved. The maximum test boundary of the NTF has also been transferred to the flight envelope on the left to show the full scale Reynolds number test capability in that format. As can be seen the tunnel will not provide full scale Reynolds number for low altitude flight of this airplane. However, the NTF does provide correct simulation in the high performance region of the envelope which includes the cruise point. This region is by far the most important region insofar as aircraft design and efficiency are concerned.

* For this figure, Reynolds number is based on 0.08 times the square root of the test section area rather than the more conventional value of 0.10.

NATIONAL TRANSONIC FACILITY EFFECT OF RN, M, AND POWER ON OPERATING COST

$$\text{LN}_2 = 80 \text{ ¢/kg } (\$70/\text{ton})$$

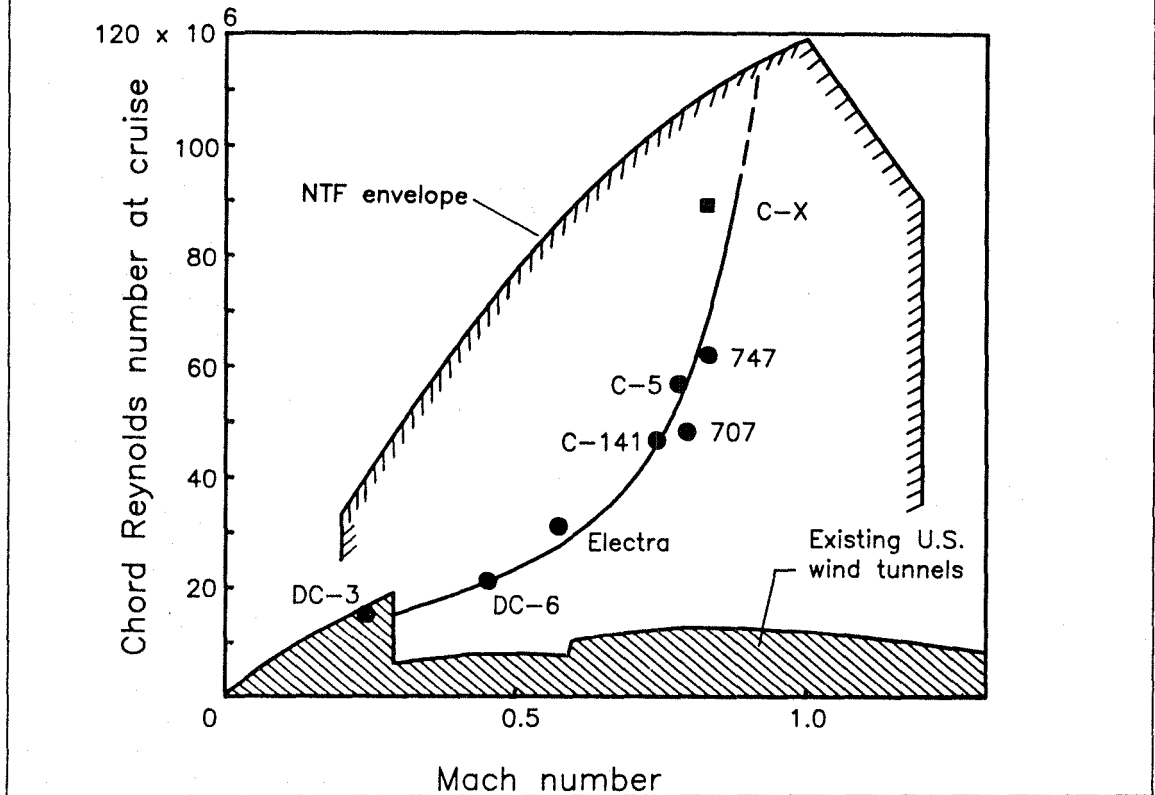


One of the major concerns expressed by most potential users of the NTF is whether or not the cost of testing will be prohibitive. This question has been addressed by a short note by Howell in "Cryogenic Technology" (ref. 24). In the note, Howell concluded that the basic operation of the NTF will be similar to any other transonic wind tunnel. The cost per occupancy hour, therefore, is not expected to be greatly different than for currently existing tunnels. Because of the attempts made to enhance data gathering efficiency, one might expect that the total tunnel occupancy cost for a given set of data could be less for the NTF.

Added to occupancy cost is the cost of the liquid nitrogen consumed in the users test program. Based on an assumed liquid nitrogen cost of \$0.80 per kilogram (\$70 per ton), the operating cost in dollars per second is presented as a function of Reynolds number in the figure above, taken from Howell's note. As can be seen, maximum cost rate is about \$30/second or about \$18,000 for 10 minutes. This cost rate is directly related to the drive power required for testing and, as would be expected, the maximum rate is at the upper operating boundary. Using this figure, it can be seen that a model of the Boeing 747 airplane can be tested at its cruise condition in the NTF at full scale Reynolds number at a cost rate of about \$10 per second or \$6000 for 10 minutes.

Thus, the Reynolds number requirements of a users test program will largely determine the liquid nitrogen costs.

The Growing Reynolds Number Gap



This chart brings us almost full circle in our Reynolds number story. On this chart, the NTF operating envelope has been added to our "Reynolds number gap" chart to show how the NTF capability very nicely closes the gap.

This chart shows that a solution to the problem of low test Reynolds number capability in transonic wind tunnels can be realized by operating the tunnel at cryogenic temperatures. The NTF at Langley has provided an order of magnitude increase in Reynolds number capability over existing U. S. transonic wind tunnels.

Other Applications of the Cryogenic Wind-Tunnel Concept

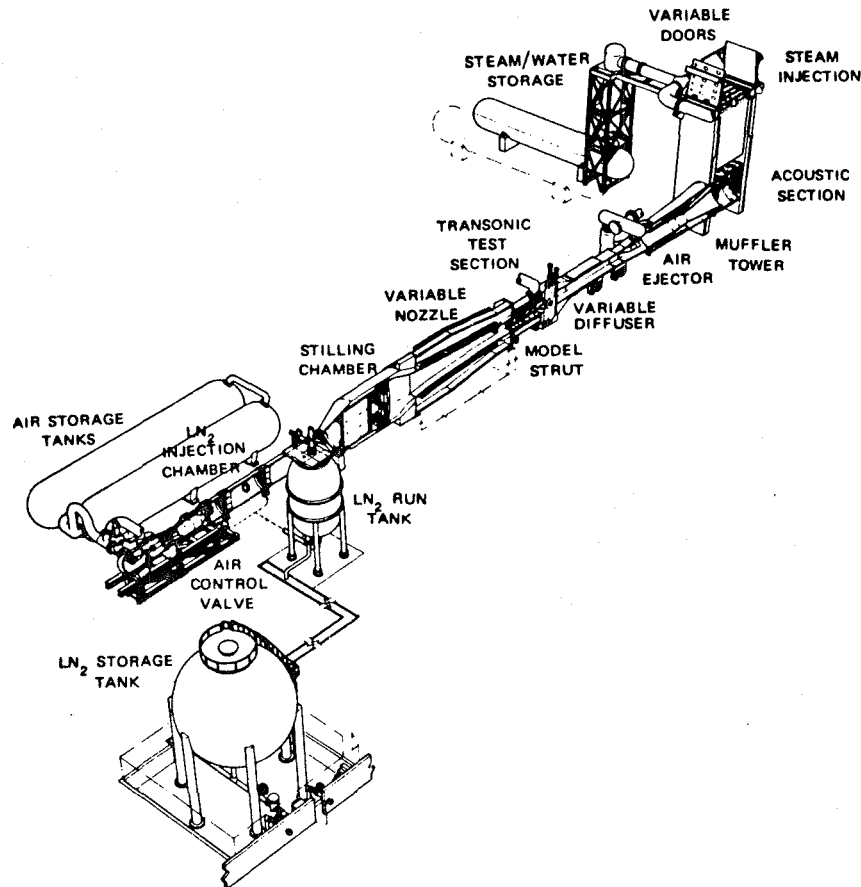
So far the discussion has been about the need for high Reynolds number testing and how a major step toward meeting that need was realized in the low-speed and pilot transonic cryogenic wind tunnel work at Langley which led, ultimately, to the NTF.

Immediately after the low-speed cryogenic tunnel work at Langley in 1972, the rest of the world took what can best be described as a "wait and see" attitude toward cryogenic tunnels. The bold decision by Langley management to proceed with a pilot transonic cryogenic tunnel was made in spite of much skepticism and some ridicule expressed by persons not fully aware of the low-speed experimental work by Dr. Kilgore or the theoretical work by Jerry Adcock which fully justified extension of the proof-of-concept studies to transonic speeds.

Following the successful development and exploitation at Langley of the cryogenic wind tunnel concept at transonic speeds in 1973, other researchers, both in the U. S. and abroad, have seen the numerous advantages of this concept and have applied it to various types of wind tunnels. The world-wide nature of the application of the cryogenic wind tunnel concept is evident in the compilation of relevant literature contained in Cryogenic Wind Tunnels - A Selected, Annotated Bibliography (Ref. 13).

Several cryogenic wind tunnel projects are described in the following pages in order to illustrate the wide variety of such projects which have arisen since the first cryogenic tunnel was built at Langley in 1972. The following section is not all-inclusive and further, very up-to-date information is available in reference 32. This includes recent information on cryogenic research facilities in China and Sweden.

Douglas Four-Foot Cryogenic Wind Tunnel

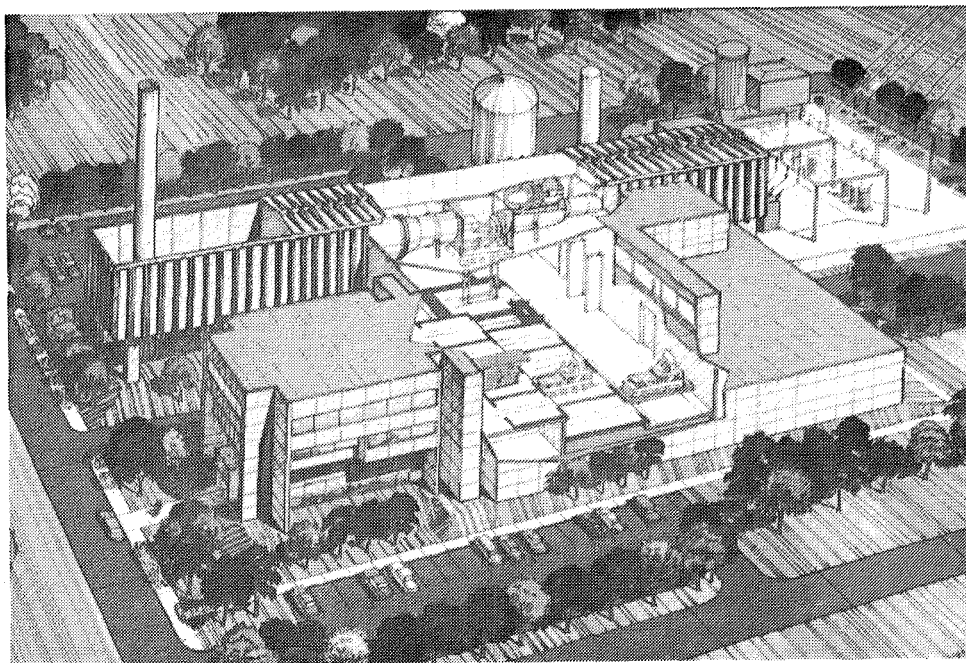


United States

The Douglas Aircraft Company modified existing 1-ft and 4-ft transonic blowdown tunnels for cryogenic operation. The 1-ft tunnel was used for a series of tests to determine the effects of nonadiabatic wall conditions on airfoil characteristics.

A sketch of the Douglas 4-ft Cryogenic Wind Tunnel is shown in the figure above. Although the 4-ft tunnel has been operated successfully at cryogenic temperatures, it has been decided not to proceed with the 4-ft cryogenic tunnel project at this time due to the cost of providing a system to thermally pre-condition the model.

A low-speed fan-driven cryogenic tunnel has been built and successfully used at the University of Illinois at Urbana-Champaign for studies of forced, natural, and combined convective heat transfer under conditions requiring very large values of both Reynolds number and Grashof number.



Europe

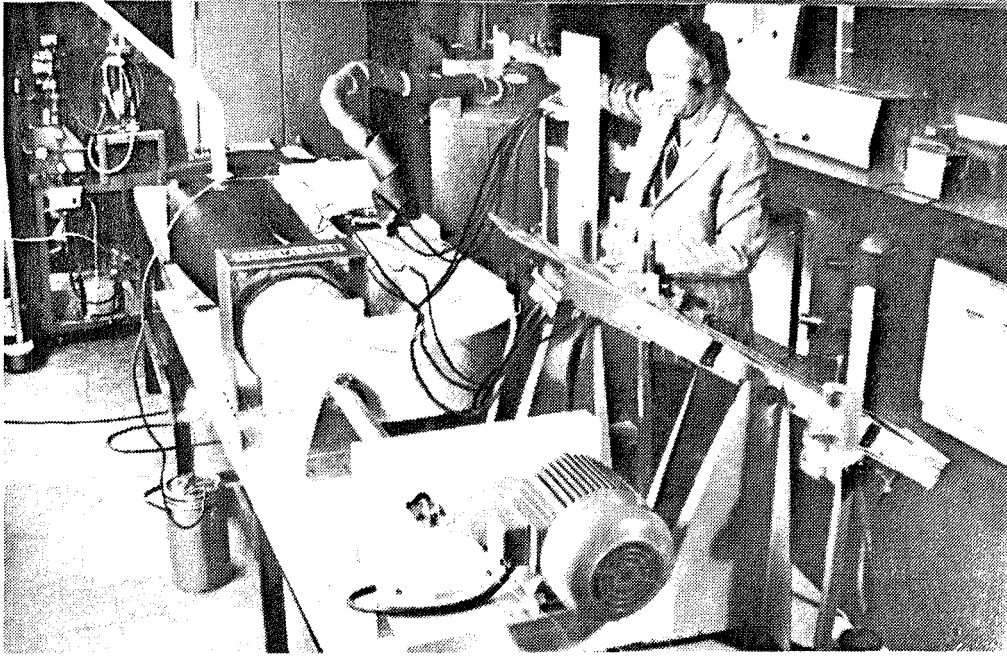
Four European countries, France, the Federal Republic of Germany, the Netherlands, and the United Kingdom, have joined together through AGARD and agreed to design and build a large fan-driven transonic cryogenic tunnel in Europe to meet their high Reynolds number testing needs.

The tunnel, to be known as the European Transonic Windtunnel (ETW), is shown in the artist's sketch above. The ETW is to have a 2.4 x 2.0 m test section and be capable of operation at Mach numbers from 0.15 to 1.3 at pressures from 1.25 to 4.5 bars. The operating temperature of the ETW will range from 90 to 320 K.

An unusual design feature of the ETW is the scheme chosen for thermal insulation. The entire tunnel is to be housed within an insulated building, thus allowing access to both sides of the tunnel structure for periodic inspection or modification.

Work on the ETW project to date includes the building of a 1:8.8 scale pilot tunnel for the ETW at the National Aerospace Laboratory in Amsterdam. The pilot cryogenic tunnel, known as PETW, has the same operating range as anticipated for the ETW. Research in support of the design of the ETW has been carried out in each of the four countries. The preliminary design of the ETW, by the Sverdrup Corporation, has been completed. The Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt (DFVLR) research center at Porz Wahn, Germany, has been chosen as the site of the ETW.

Low-speed Cryogenic Wind Tunnel University of Southampton

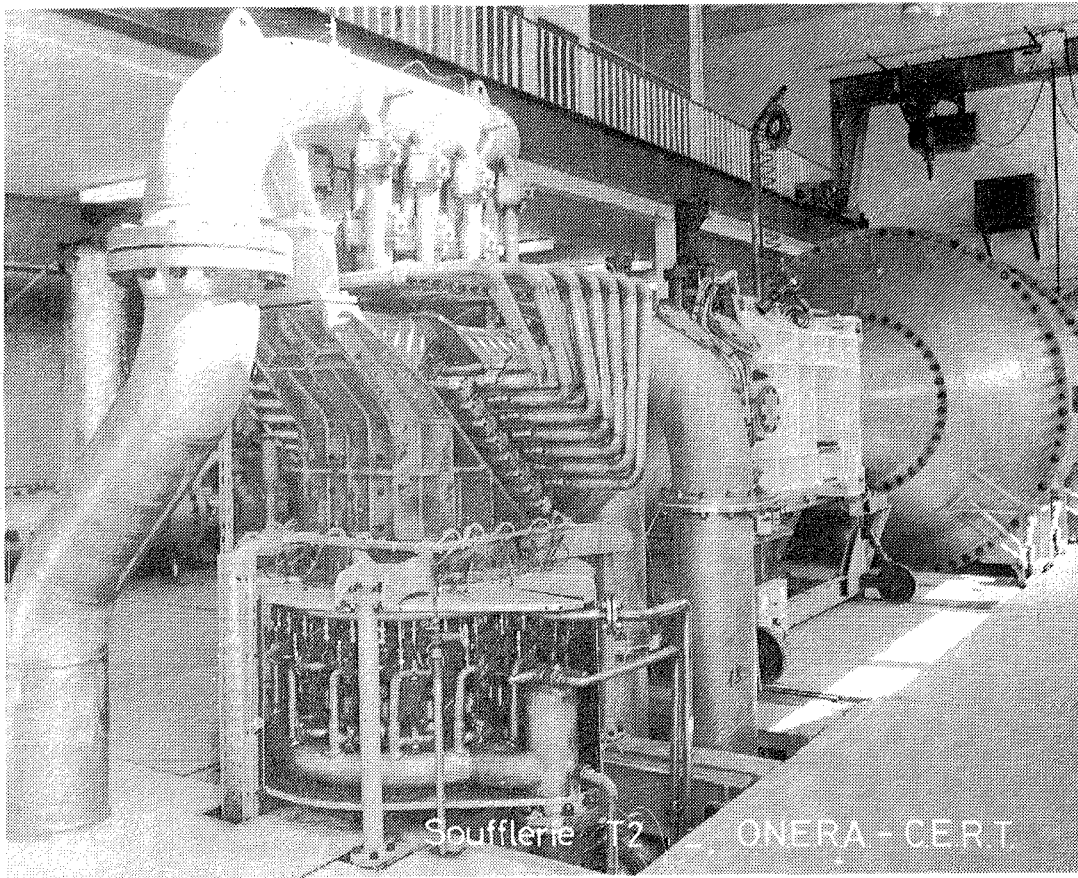


England

At The University of Southampton, under the direction of Dr. M. J. Goodyer, a low-speed fan-driven cryogenic tunnel having a 0.1 x 0.1 m test section has been built and successfully operated in conjunction with a magnetic suspension and balance system.

A pilot intermittent cryogenic wind tunnel based on the use of an expanding high pressure gas and a free piston has been demonstrated by Professor Stollery and his co-workers at the College of Aeronautics, Cranfield.

A closed circuit Cryogenic Test Duct has been constructed at the Royal Aircraft Establishment (RAE), Bedford, under the auspices of Mr. Law and his co-workers, as part of the United Kingdom support for the European Transonic Windtunnel (ETW) program. The Test Duct is used as an inexpensive and convenient way of providing a cryogenic environment for testing wind tunnel balances and model components under realistic conditions of gas flow. The maximum gas velocity through the 0.3-m square test section is 25 m/s, falling with temperature. By controlling the rate of injection of LN_2 in the circuit, the gas temperature can rapidly be reduced and controlled at any level between ambient and 90 K. A more detailed description of the work in England is presented in reference 32.



France

Following development work in a small pilot tunnel, T'2, an injector driven tunnel, T2, at the ONERA Research Center at Toulouse has been fitted with a 0.4 x 0.4 m adaptive wall test section and successfully modified for cryogenic operation. A complete description of this work, including test results obtained at high Reynolds numbers on a Cast 7 airfoil, is given in reference 33.

Additional cryogenic wind tunnel activities in support of the ETW project have been carried out in France by ONERA-CERT using both low-speed and transonic cryogenic wind tunnels.



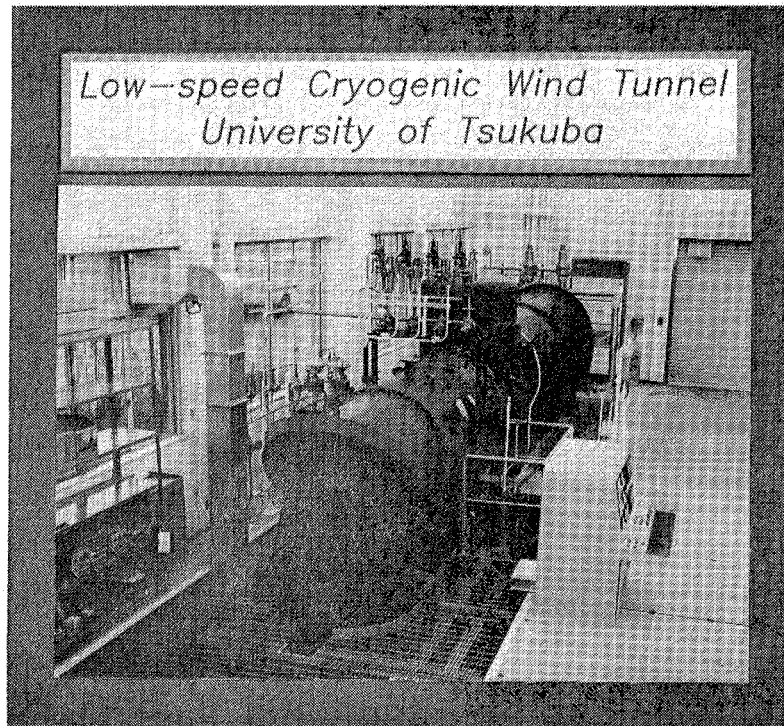
Germany

Outstanding progress has been made by Dr. Viehweger and his co-workers at the DFVLR Porz-Wahn Research Center on the modification of a large low-speed fan-driven tunnel for cryogenic operation (See reference 34.) The project started in the autumn of 1978 with studies of how to modify the 3 m low-speed wind tunnel at Koln for cryogenic operation. The studies were completed in 1979 and the go-ahead for the project was given in 1980. Design and construction of the facility was completed in March of this year. Cryogenic operation and checkout of the tunnel began in January of this year.

The tunnel, known as Kryo-Kanal-Koln (KKK) has a 2.4 m x 2.4 m test section and, because it is made of concrete, has been carefully fitted with internal insulation. The maximum Mach number of the KKK will be 0.38 when operating at the design minimum temperature of 100 K. An aerial photograph of the KKK is shown in the figure above.

A feasibility study was performed at DFVLR in 1982 to determine the type of tunnel best suited for high Reynolds number research at transonic speeds taking into account requirements regarding size, performance, and budget limitations. The resulting decision to build a cryogenic Ludwig-tube driven tunnel at the DFVLR Research Center in Gottingen was approved by the Board of Directors of the DFVLR in the autumn of 1982. The tunnel is in the final stages of construction with delivery of the diffuser/fast-acting valve scheduled for the winter of 1985-86.

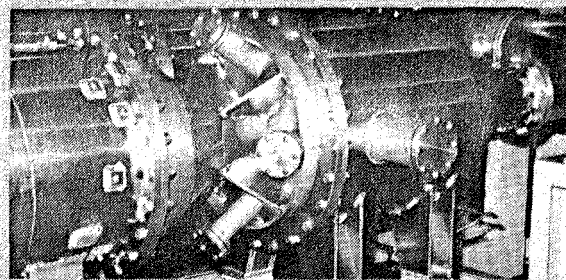
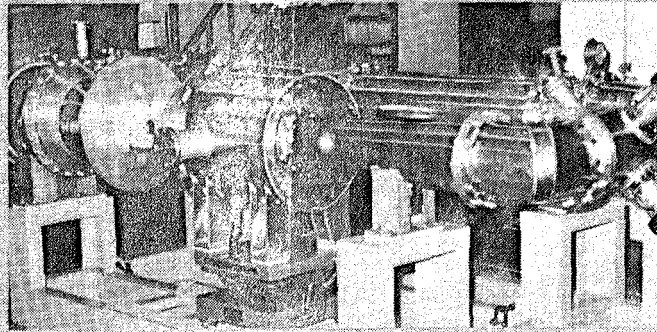
The tunnel is designed to operate at Mach numbers from about 0.2 to 1.2 and provide Reynolds numbers up to 70 million based on a 0.15 meter chord.



Japan

A low-speed cryogenic tunnel, designed by Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI), has recently been completed and placed in operation at the University of Tsukuba. The fan-driven tunnel has a 0.5 x 0.5 m test section and operates at pressures up to 8 bars. Liquid Nitrogen storage is in a 20,000 liter stainless steel tank. This cryogenic tunnel is unusual in that the pressure shell is mostly of mild steel which is protected by an internal insulation system. A further innovation at Tsukuba is the use of aluminum casting for construction of the test section, contraction, and diffuser.

*10 x 10 cm Transonic Cryogenic Wind Tunnel
National Aerospace Laboratory*



A small transonic cryogenic tunnel has been designed and built for the Japanese National Aerospace Laboratory (NAL) in Tokyo and has recently been placed in operation. The fan-driven tunnel has a 0.1 x 0.1 m test section. The pressure shell is of welded aluminum alloy construction with external insulation and can be operated at pressures up to 2 bars.

The small transonic cryogenic tunnel at NAL is being used to provide operational experience and support their design studies of a much larger transonic cryogenic tunnel for Japan.

Problems Common to Wind Tunnels

✓ Low Reynolds number

Flow unsteadiness

Wall interference

Support interference

ABRL pdm 5-2-84

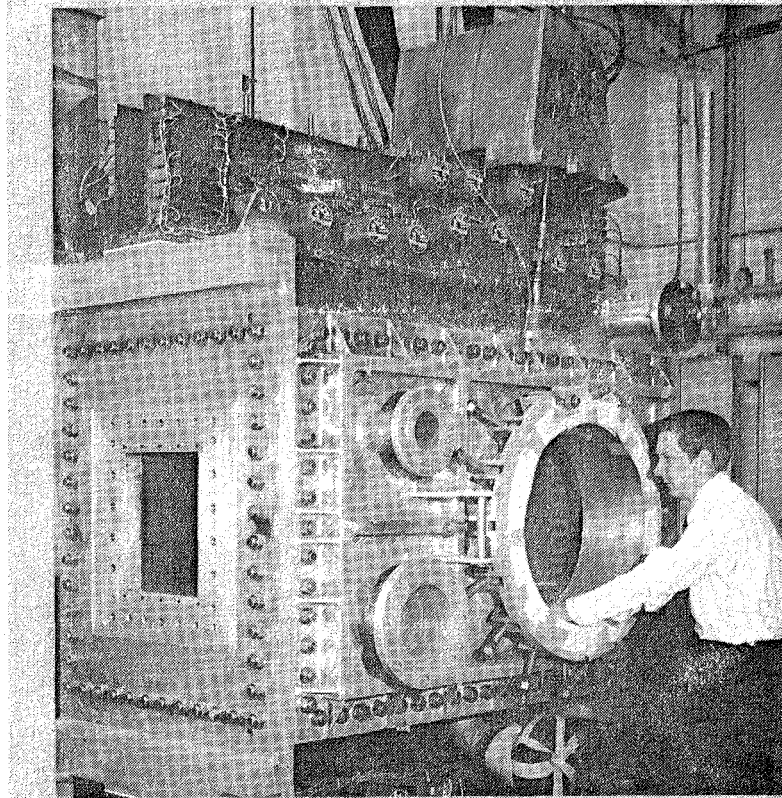
As has been shown, the development of cryogenic wind tunnels has made it possible to test sub-scale models of many important aerodynamic configurations at full-scale Reynolds number in tunnels of reasonable size at reasonable operating pressure. This is the reason for the check mark beside "Low Reynolds number" on the figure shown above, which as you will recall, was used earlier to introduce the major problems related to wind tunnel testing.

Significant advances have also been made in our ability to measure and quantify flow unsteadiness and in our understanding of the effect of flow quality on various types of aerodynamic data.

Progress has also been made in improving the flow quality in wind tunnels such as the Langley 8 ft Transonic Pressure Tunnel through, for example, modification to existing tunnel hardware. New tunnels, such as the NTF, are being designed to incorporate, insofar as possible, features known to contribute to good flow quality.

The two remaining problem areas, wall interference and support interference, are being addressed with varying degrees of vigor at many of the aeronautical research establishments around the world. At NASA - Langley we are very actively involved in both of these areas seeking solutions that, in their ideal implementation, will be compatible with cryogenic wind tunnels.

0.3-m TCT Flexible-Wall Test Section



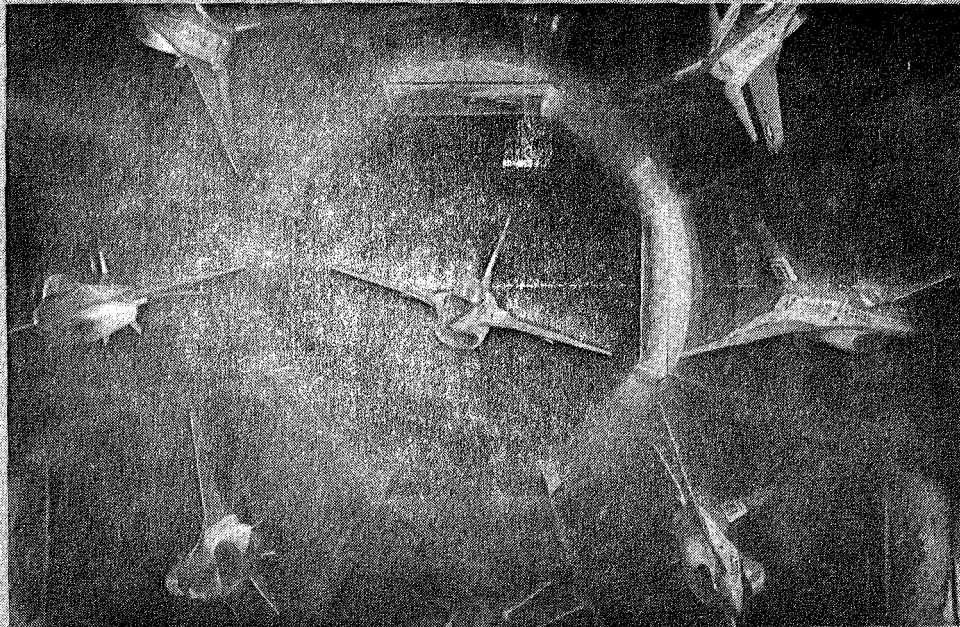
Shown in the above photograph is a 13" by 13" test section fitted with solid self-streamlining top and bottom walls. This rather robust looking test section has been installed in the 0.3-m TCT circuit and when check-out and calibration are complete, this test section will allow us to test airfoils with chords up to 12" or so at Reynolds number up to 120 million.

At the top of the photograph can be seen some of the stepper motors which, responding to computer control, drive 21 jacks per wall. The entire process is controlled by a dedicated minicomputer which, through the appropriate algorithms, automatically adjust the top and bottom walls to streamline shapes. The large opening in the side of the plenum provides model access while the various smaller flanged pipes provide side-wall boundary removal and instrumentation access.

Although our in-house effort in self-streamlining wall research is considerable, especially in terms of hardware development and application, additional work in this area is being funded by NASA - Langley at The University of Southampton under the direction of Mike Goodyer.

Even though the ability to test airfoils at full-scale Reynolds number free of wall interference is very important, the ultimate aim of this research is to develop the technology to allow us to use solid self-streamlining walls for testing three-dimensional models in much larger tunnels. For example, tunnels the size of the NTF.

Model of F-16 in M.I.T. MSBS

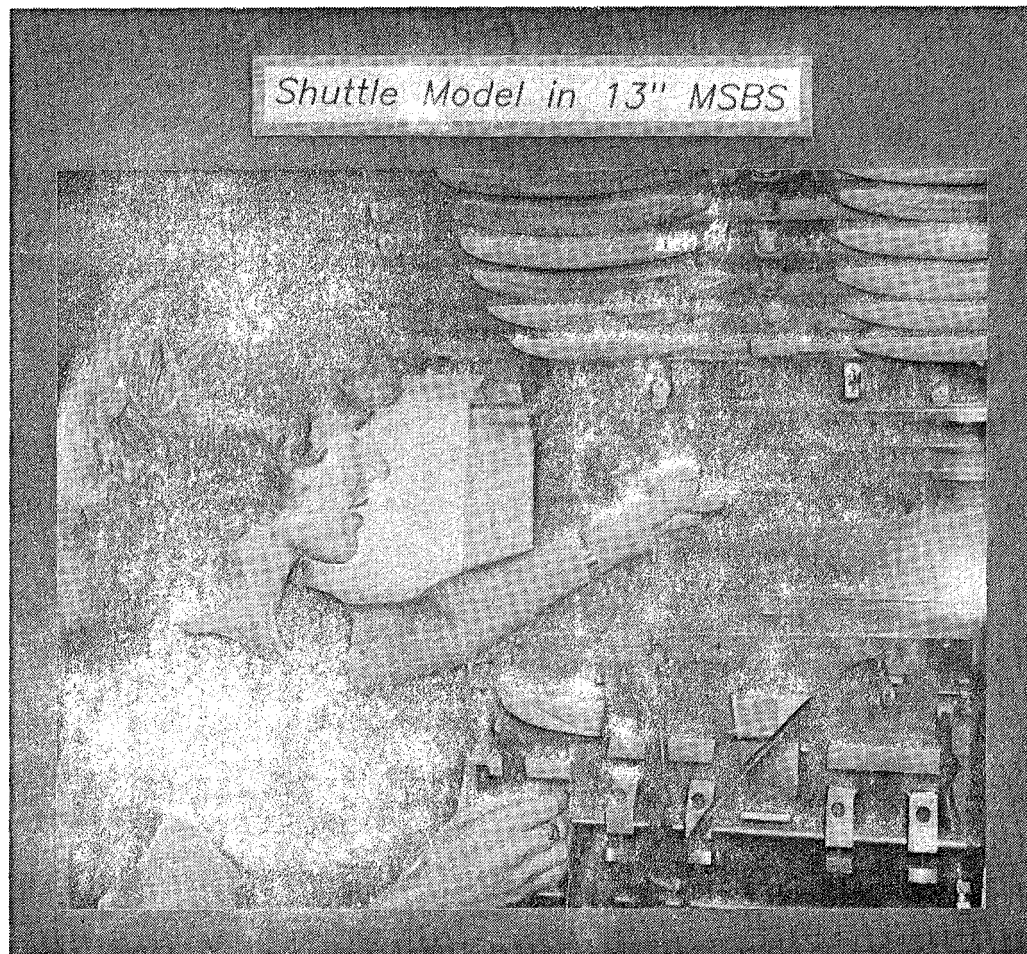


Short of actual flight or range testing, there appears to be only one solution to the problem of model support interference, namely, the use of magnetic forces to suspend the model in the test section.

This type of support requires the model to be made of magnetic material or to have a suitable magnetic core. Typical cores are made either from soft iron or some permanent magnetic material, or as recently demonstrated, an isolated superconducting magnet. With proper attention to detail, the currents in the electromagnetic coils used for suspension can also be used to provide accurate measurement of the aerodynamic forces and moments acting on the model.

The above photograph illustrates one of the many advantages of a magnetic suspension and balance system (MSBS), namely, the complete absence of any physical model support system. Impossible to illustrate in a still photograph is the fact that an MSBS also allows almost unlimited model orientation as well as almost unlimited but accurately controlled model motion in all degrees of freedom.

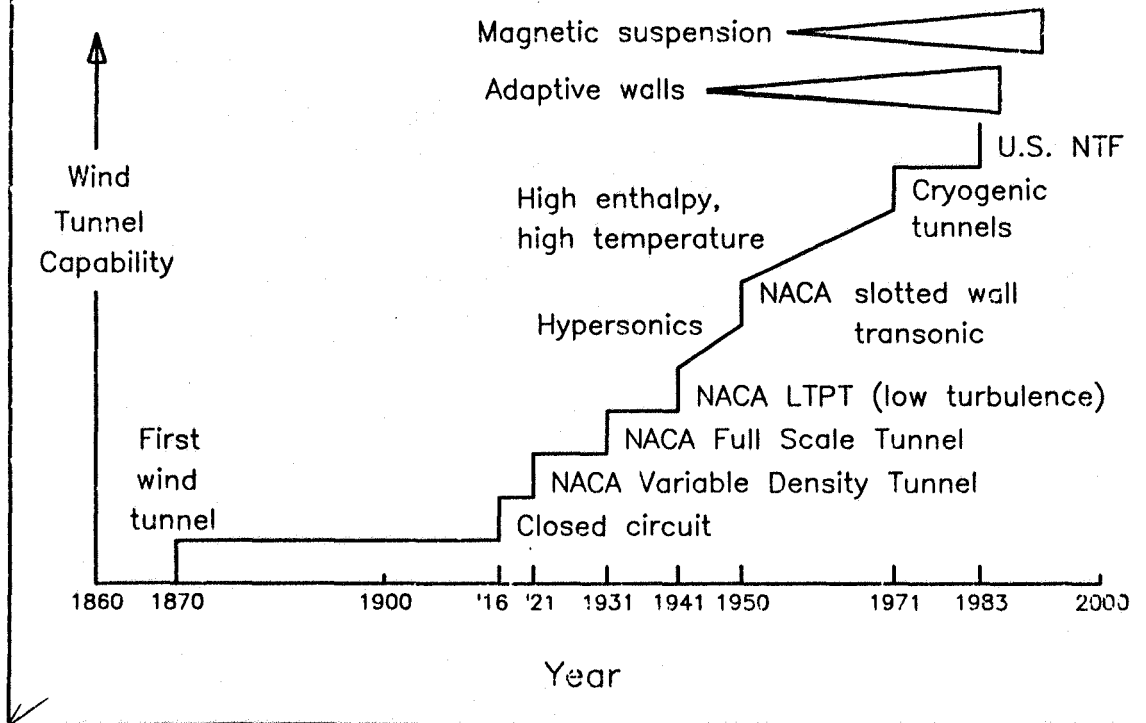
The 6" MSBS in the above photograph has recently been moved from M. I. T. and has been re-assembled by personnel of our Instrument Research Division at Langley. This system will be used in our in-house program to develop MSBSs capable of being used in much larger wind tunnels, again, tunnels the size of the NTF or larger.



A 13" MSBS was built several years ago at AEDC and used to study wakes from various bodies at hypersonic speeds. This system, which has the distinction of being the largest MSBS in the world, has been moved to NASA - Langley where it has been adapted to a low-speed wind tunnel.

The 13" system has recently been placed into operation and will be used for both aerodynamic testing and to support our in-house MSBS development program.

Quantum Improvements In Wind Tunnels



In order to forecast where we may be in the future with respect to wind tunnel testing capability, it is interesting, and possibly helpful, to look at the past and examine some of the major steps that have been taken to get us where we are today, 115 years after Wenham built the first wind tunnel.

The above chart, which is mostly self explanatory, shows some of the major steps between Wenham's tunnel and the NTF which is generally acknowledged to represent the highest standard in transonic testing capability today, even by researchers not from the Langley Research Center.

Magnetic suspension of wind tunnel models has been around since the work in France at O. N. E. R. A. in the 1950's. Adaptive, or at least deformable, test section walls have been in use since the work at the British National Physical Laboratory in the mid 1940's. Therefore, these concepts are shown as triangles, offering since their first development "potential improvements" to wind tunnels. The technologies needed to successfully realize both of these concepts have only recently been developed to the point where serious consideration could be given to actually incorporating them into a large transonic wind tunnel.

Obviously, we are of the opinion that the next two major improvements in wind tunnel testing capability will be made through the application of self-streamlining or adaptive wall test sections and magnetic suspension and balance systems.

The Future

- * Wind-tunnel results will be obtained at the proper Reynolds number.
- * Will eliminate or greatly reduce effects of –
 - flow unsteadiness
 - wall interference
 - support interference

NTF-30 pdm 12-5-83

Based on what has already been demonstrated in a number of cryogenic wind tunnels, including the 0.3-m TCT and the NTF, in the “ideal” wind tunnel of the future the aerodynamic researcher will obviously be able to test his models at the proper Reynolds number.

Furthermore, by taking full advantage of emerging technologies, in our ideal wind tunnel we will also have either completely eliminated or reduced to acceptable levels the undesirable effects of flow unsteadiness, test-section wall interference, and model support interference.

Once this ideal tunnel is realized and put into use, we should be able to greatly improve our understanding of basic aerodynamics as well as develop new vehicles without having to spend our time applying “corrections” to the wind tunnel data.

APPENDIX

Recent Progress in Cryogenic Testing

Techniques

at

NASA Langley

Note:

This section contains citations of new technology too numerous for the individual description of each one. Also, many of the items are so new that there is no formal documentation or even completed data analysis. An effort was made to include at least a mention of each item in order to make this presentation as current as possible. The test techniques are categorized with a compilation page for each category. Each technique is listed with information about its status and the type of information to be found about that technique.

Recent Progress in Cryogenic Test Techniques

Airfoil Testing

Airfoil test with sidewall boundary layer bleed.

Data chart follows.

Oscillating airfoil testing.

Data reduction still underway; photograph follows.

Drag coefficient mapping of three dimensional wakes by pitot surveys.

Three dimensional wake topology of a two dimensional cylinder is shown on a following chart.

Simultaneous static and fluctuating wake pressure surveys.

Data reduction still underway.

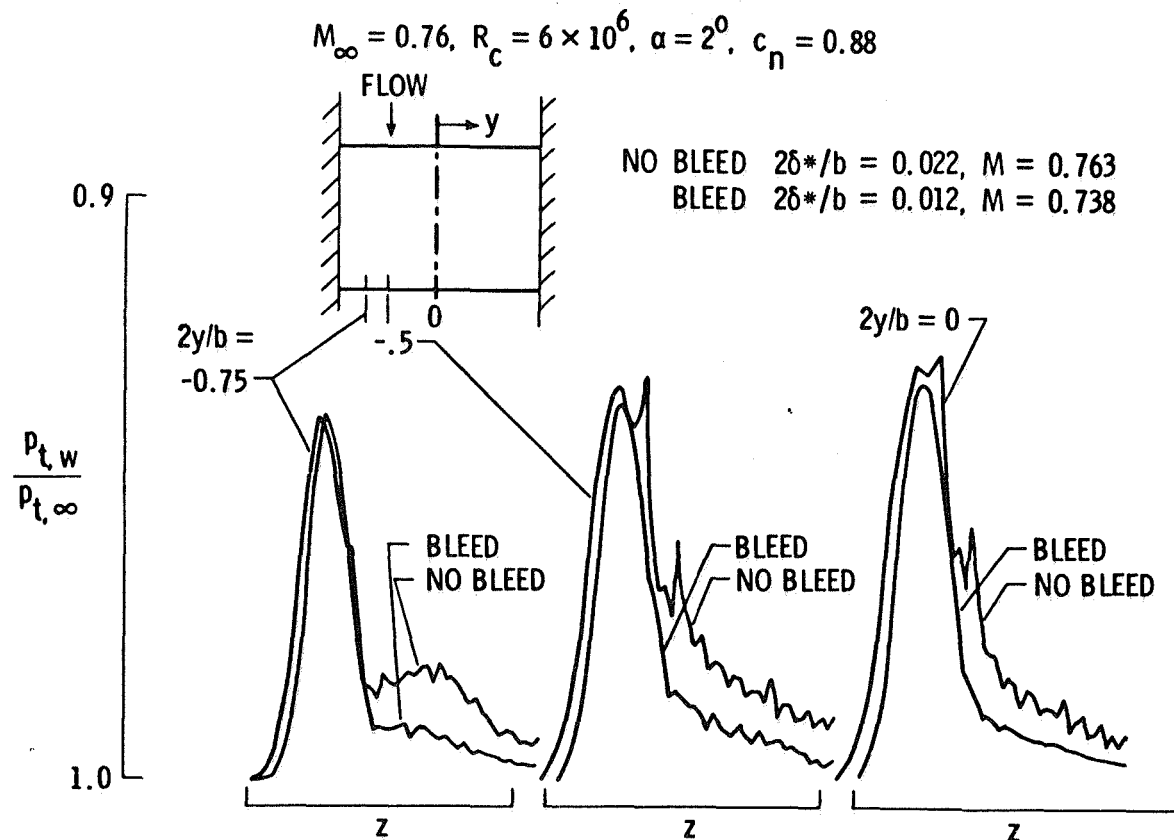
New construction technology for airfoil models:

Adhesively bonded cover plates (see ref. 19).

Steel pressure tubes cast in fiberglass airfoil (successfully tested, data reduction in process).

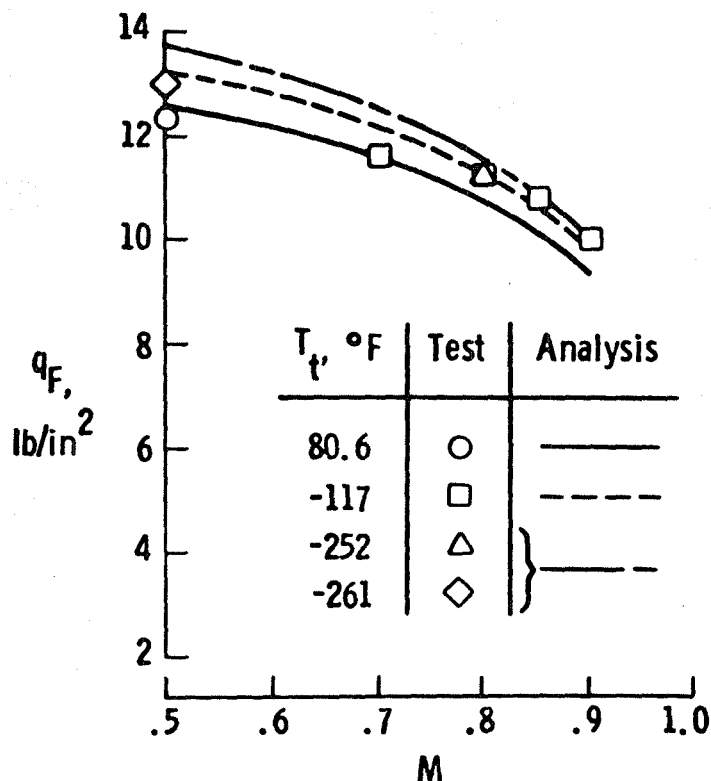
Integral pressure passages between bonded plates, photograph follows.

Electrical discharge wire cut of airfoil contours (see ref. 18).



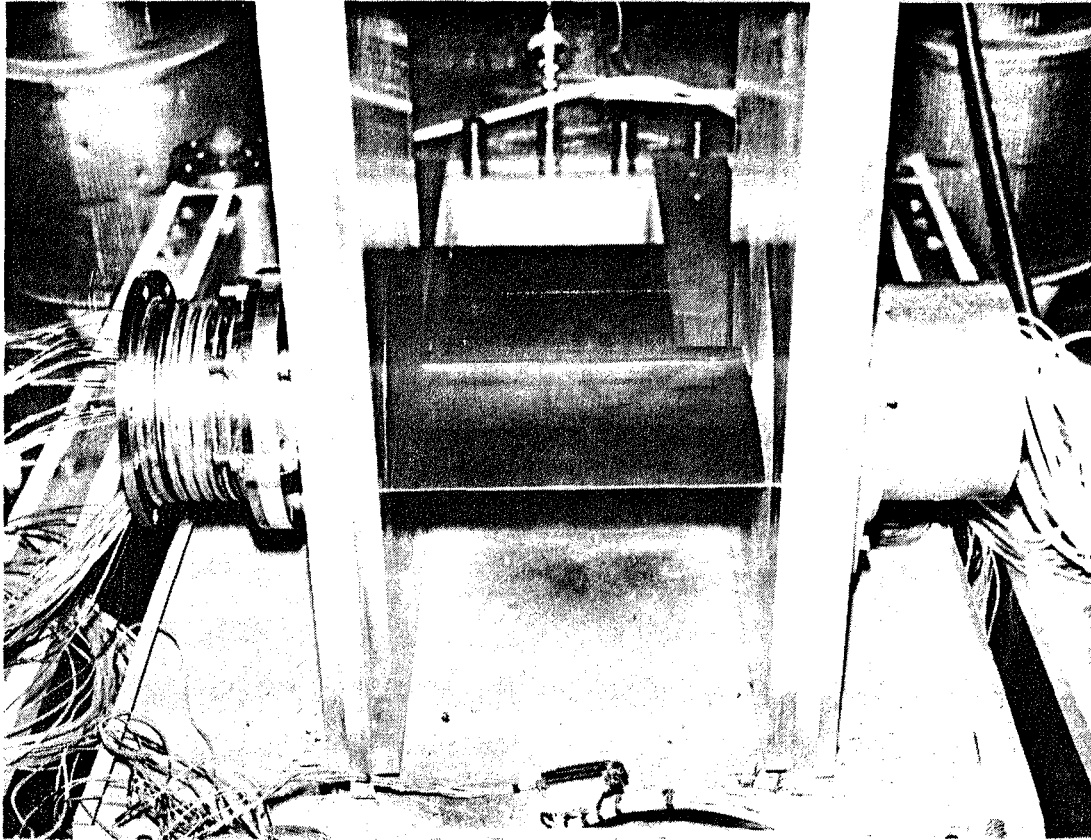
Airfoil Test With Sidewall Boundary Layer Suction

This chart shows pressure surveys through the wake of a 12 percent thick supercritical airfoil at three spanwise stations. Results are shown with and without "suction". The term suction here refers to the tunnel sidewall boundary layer having been treated just ahead of the model by suction to remove some of the low energy boundary layer fluid. This action has the effect of increasing the boundary layer's resistance to separation, allowing it to behave more like the free stream flow. This effect is more succinctly expressed by the reduction in shape factor, as shown in reference 23. The case presented is for high lift and a transonic shock. The Gaussian shaped part of the curve is due to the viscous drag losses and the ragged ramp portion is due to the shock losses. The use of boundary layer bleed smoothes the wake distributions, especially the shock loss part of the curve, as well as making the shape of the curves more uniform in the spanwise direction. Additional, more detailed, information is contained in reference 14.



A flutter test has been conducted in the 0.3-m Transonic Cryogenic Tunnel to explore problems, develop testing techniques, and determine the potential of a cryogenic tunnel to advance the state of the art in flutter testing. A simple "text book" rectangular planform wing model supported by a beam flexure was used for the test. Model and support were machined from a single piece of material, and 18 Nickel grade 200 maraging steel (trade name Vascomax 200). This material is characterized by its good dimensional stability with temperature change and its high cryogenic temperature fracture toughness. Although no "hard" flutter points were included in the test, the model oscillations were large enough to be easily visible on a video monitor at conditions near flutter onset.

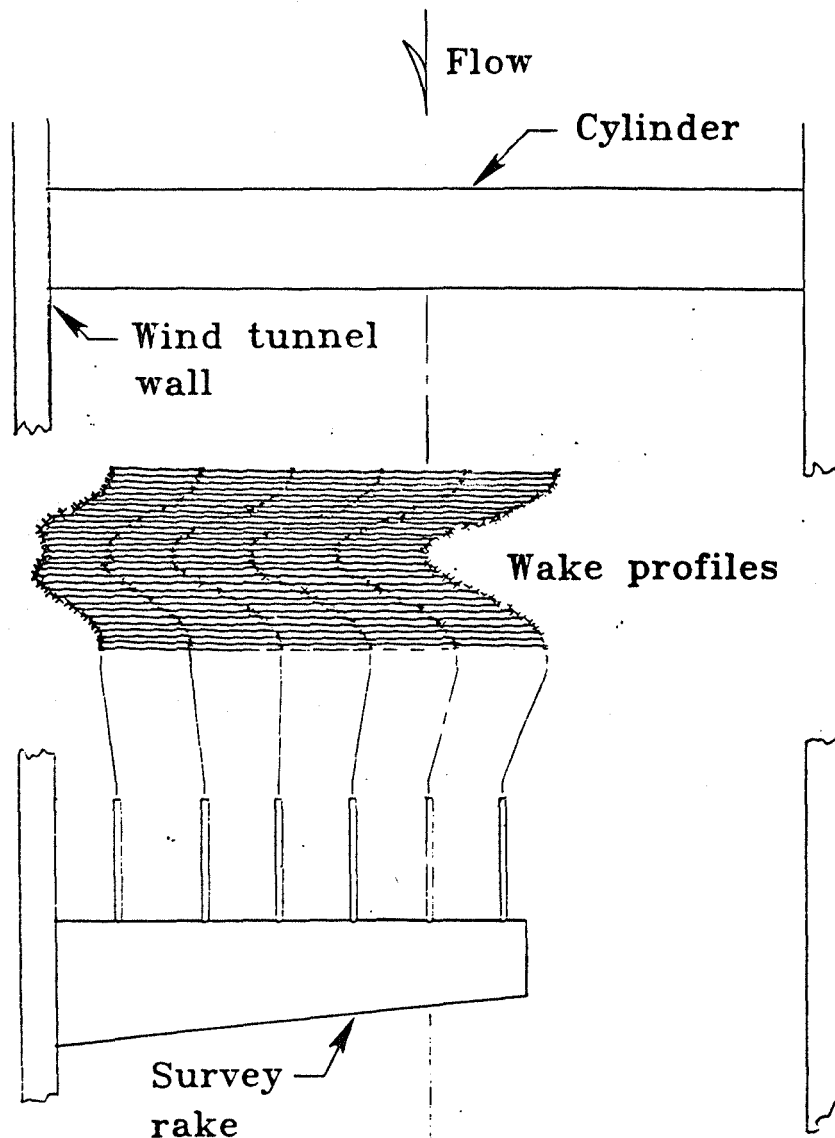
The figure on this page presents a comparison of analytical and experimental flutter results in terms of the flutter dynamic pressure as a function of Mach number. It is presented here only to illustrate flutter data taken at cryogenic temperatures, and was taken from AIAA Paper No. 85-0736. Further details including the effect of Reynolds number on transonic flutter are also contained in this reference.



Oscillating Airfoil Testing

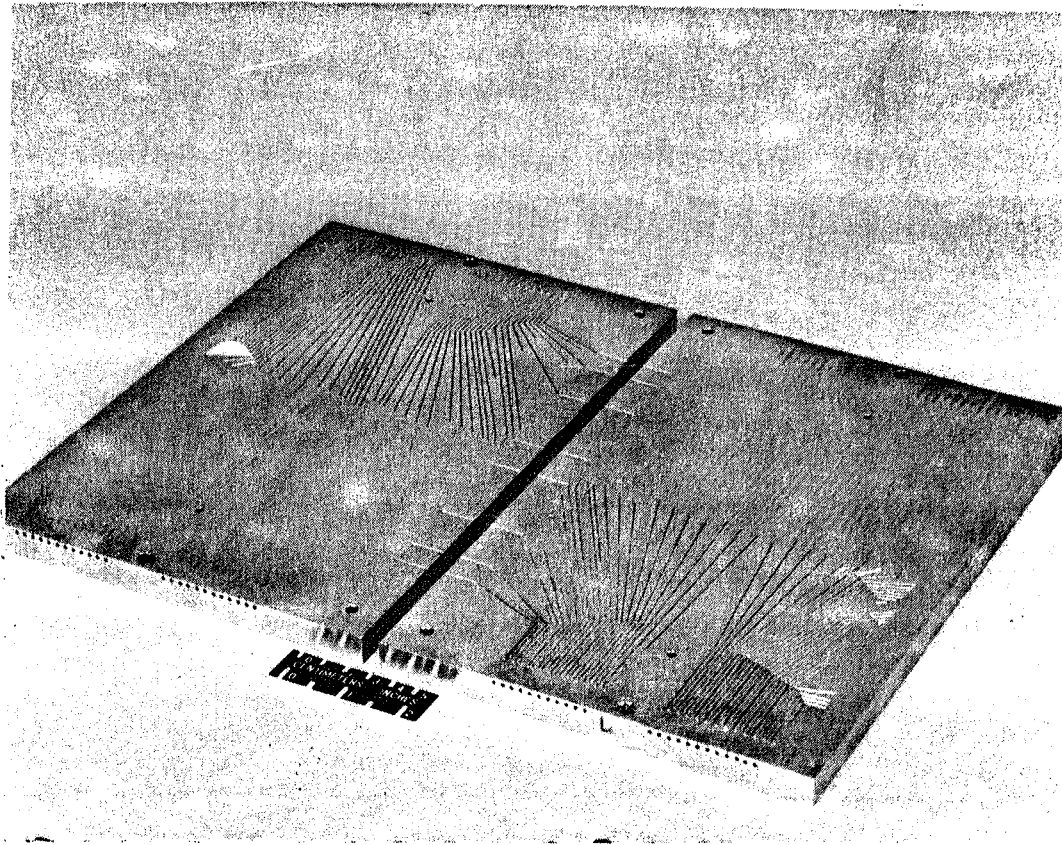
The above photograph shows the 14 percent supercritical airfoil model mounted in a test section module of the 0.3-m TCT. The model is being viewed from the trailing edge. The drive bellows that transmitted the torque to oscillate the model from an external actuator is visible attached to the left wall of the module. The model was oscillated at frequencies as low as 4 cycles per second, and as high as 60 cycles per second. Amplitudes were as low as $\pm 1/4$ degree and as high as ± 1.0 degrees. Tests were conducted at cryogenic temperatures and well into the transonic speed range. Fluctuating pressure data was measured by 43 pressure transducers mounted internal to the model.

This data will be helpful in the understanding of unsteady aerodynamic processes including flutter, buffet, and rapid changes in pitch.



Three Dimensional Wake Topology

This sketch illustrates a technique of creating a topology of the momentum loss in the wake of a body, in this case a cylinder. Wake surveys with a rake of pitot tubes are a conventional method of determining the momentum loss, and thus, the drag of a body. The data here were obtained by an updated version of this method where the survey rake is driven through the wake by a computer controlled actuator, and there are six tubes, rather than the conventional one tube, which allow determination of the spanwise variation in the wake. Not only does conducting such a survey provide additional data, but doing so in a cryogenic environment is a major engineering achievement. This particular sample illustrates the classic Gaussian shaped curve for those tubes near the tunnel centerline, and shows deviations from this shape at stations close to the wall. This is due to the interaction between the wall boundary layer and the cylinder.



New Construction Technology For Aircraft Models

Building models for the new class of cryogenic tunnels requires a combination of advanced and new technologies. In order to isolate the sought after Reynolds number effects from surface roughness induced effects, it is necessary to have very good surface finish (6 to 8 microinches at the leading edge). Unusual materials are utilized to provide the necessary fracture toughness at cryogenic temperatures. Exceptionally good dimensional stability is required during temperature cycling to maintain the accuracy demanded of transonic models. These requirements, together with the required high strength, make the task of building the necessary models nearly impossible, leading to lost research time and high model costs. The technique pictured above is one of the new solutions being researched to alleviate the model construction problem for pressure instrumented models. Here, the pressure channels are cut or etched into the opposing faces of a metal "sandwich"; the sandwich is closed and brazed together in a vacuum oven resulting in a model "blank" with high strength and low "plumbing" costs. This model has been built and successfully tested. Further details may be found in references 17 and 18.

Recent Progress in Cryogenic Test Techniques

Aerodynamic Testing Techniques

Use of a cryogenic compressor

The use of a compressor to pump flow from the plenum or to remove sidewall boundary layers is common practice in many transonic tunnels. This task has now been accomplished in a cryogenic tunnel. Operation is explained in a sketch and a chart.

Diffuser choke plate studies.

Data reduction still underway.

Unsteady pressure measurements on tunnel sidewalls.

A sample is presented of tunnel sidewall fluctuating pressures as a function of tunnel temperature.

Measurements of free stream turbulence by 3-wire hot wire probes.

See AIAA Paper 83-0384. (Ref. 20)

Transient temperature technique to allow determination of transition location by measurement of heat transfer.

Data reduction still underway.

Measurement of flow dynamics in the settling chamber.

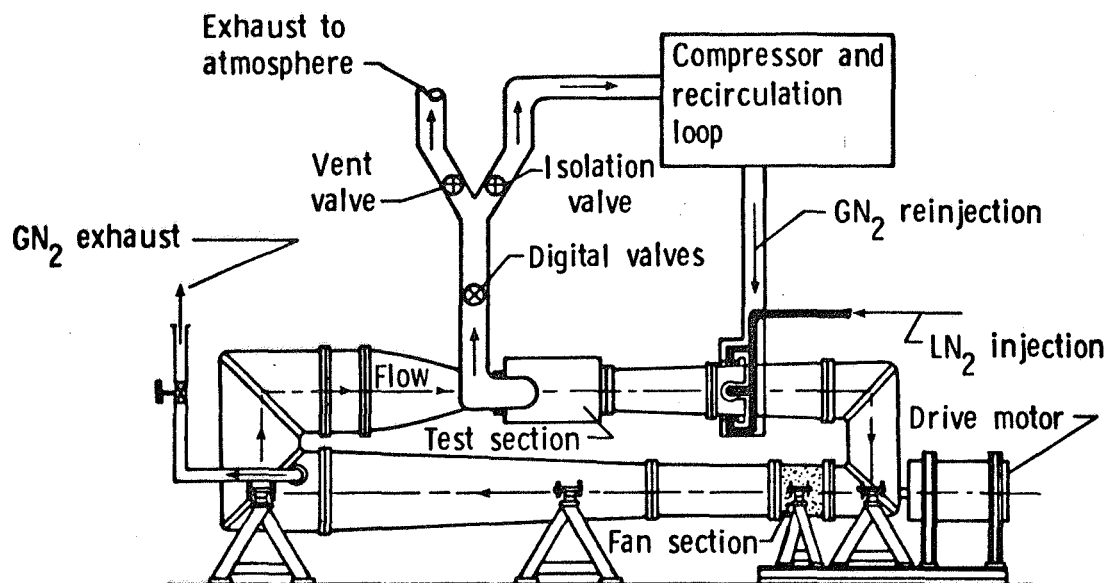
See AIAA Paper 84-0596. (Ref. 21)

Measurements with a strain-gage balance.

Photograph follows.

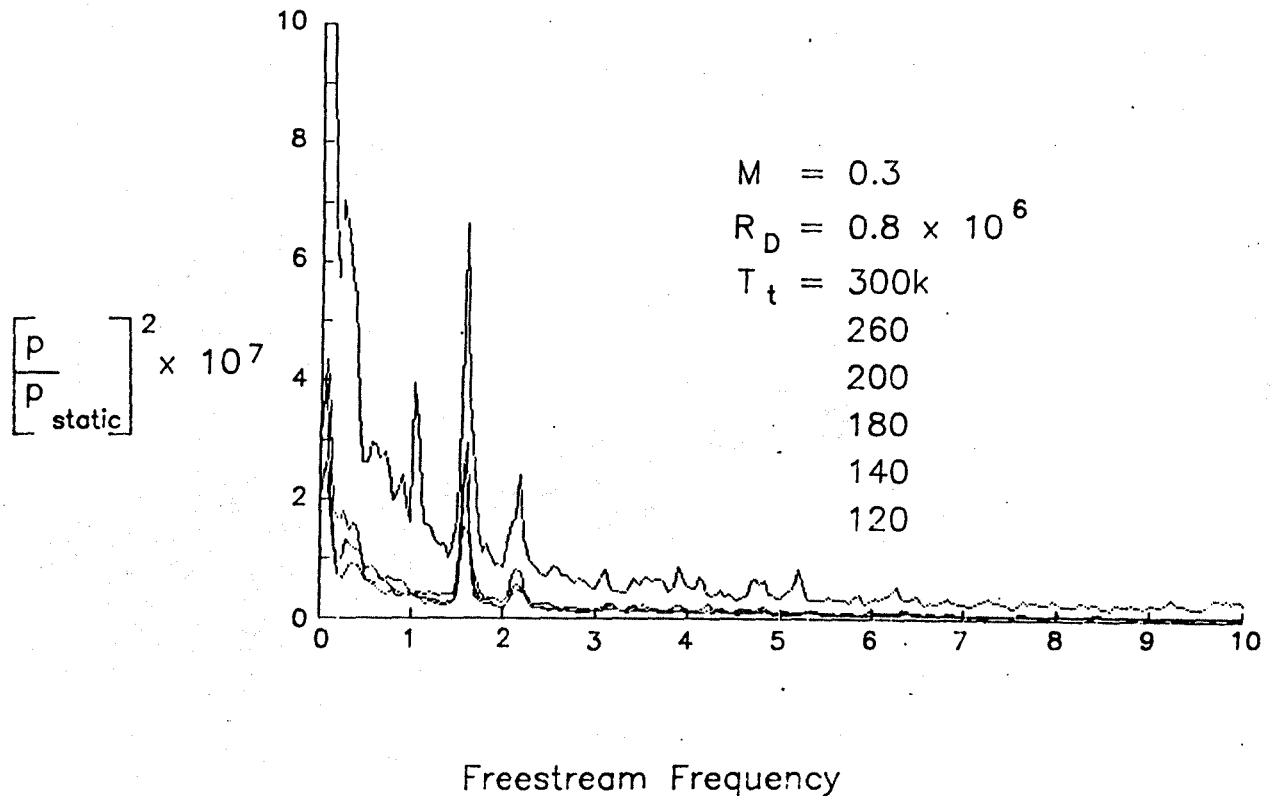
Optical methods.

Photograph follows.



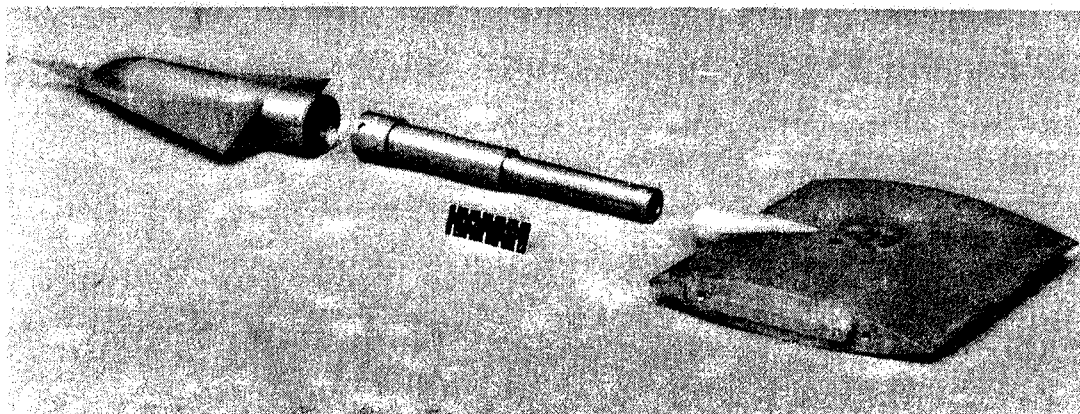
Use of a Cryogenic Compressor With The 0.3-m TCT

This schematic shows a cryogenic compressor linked with the test section region of the 0.3-m TCT. The compressor is required to operate over a wide range of pressures and temperatures, including cryogenic temperatures as low as 80 K (-320°F). Since the tunnel test flow is nitrogen gas, and the only supply is liquid nitrogen, a complex set of controls had to be incorporated to provide simultaneous temperature level, heat balance, and mass flow balance. Not only is this a significant engineering achievement in its own right, but the use of the compressor greatly enhances the tunnel's research capabilities. Also, since low energy air can be removed from the test section, the tunnel can be operated at higher Mach numbers. But most important for two dimensional airfoil research, is the capability to treat the test section sidewall boundary layers with suction to reduce sidewall interference.



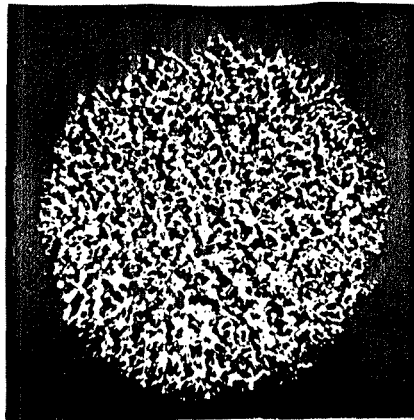
Cryogenic Fluctuating Pressure Measurements

Measurements of fluctuating pressure, shown here as a ratio of fluctuating pressure to static pressure squared, have been made on the test section sidewall of the 0.3-m TCT. The results are plotted as a function of normalized frequency to remove the effect of free stream velocity changes. A perfectly quiet tunnel would have no fluctuating pressures at the wall, but all tunnels have some "noise". Note that the pressure levels shown here must be divided by ten million which means that there is a very small fraction of the total flow energy resident as noise. One of the most interesting features of this data is the rapid reduction in the noise intensity with reduced tunnel temperature.

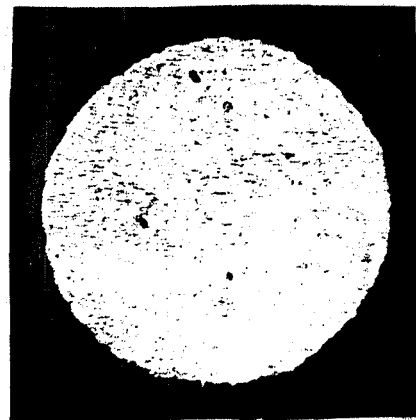


Force Measurements With a Strain-Gage Balance

Although the 0.3-m TCT has been equipped with a special test section for two dimensional airfoil testing in recent years, it is possible to do small scale three dimensional testing as shown above. Here an airfoil shape is used to support a sting and a conventional 3-D model arrangement. The strain-gage balance is shown between the model and the 2-D support. The balance was tested at cryogenic temperatures with and without electrical resistance heaters, achieving good results in both cases. Further details are contained in reference 22.



Test section + plenum



Test section only

$T_t = 100 \text{ K}$

$P_t = 5 \text{ atm}$

$M = 2.0$

Optical Methods

Various flow diagnostic and visualization techniques have been tried in the 0.3-m TCT both to enhance the research utility of the tunnel and to explore the problems and opportunities offered by cryogenic testing. The use of the Laser Transit Anemometer to survey velocity distributions in flow fields and boundary layers is described elsewhere in this paper. Other methods include laser holograph interferometry, schlieren, shadowgraph, image quality studies, and moire deflectometry measurements. All have been successful to some extent. One major problem that was encountered was a swamping of the flow features by an optical disturbance that strengthened as the tunnel temperature was lowered. This problem was isolated and identified as thermal inhomogeneities external to the test section, primarily due to convective currents in the plenum chamber. The optical degradation becomes more severe with decreasing temperature and increasing pressure, and exhibits a (p/T^2) dependence. Figure 10 shows a comparison of optical quality before and after isolation of the optical beam from the plenum. This problem is discussed in more detail in reference 35.

Recent Progress in Cryogenic Test Techniques

Fluid Mechanics

Two-spot laser boundary layer survey

Velocities measured at several points in the boundary layer of a cylinder transverse to the flow. Sample data plot follows.

Testing of controlled nonadiabatic airfoils

Transition detection

Dynamic pressure transducers placed inside an airfoil clearly show laminar, turbulent bursts, and fully turbulent flow. Data samples follow.

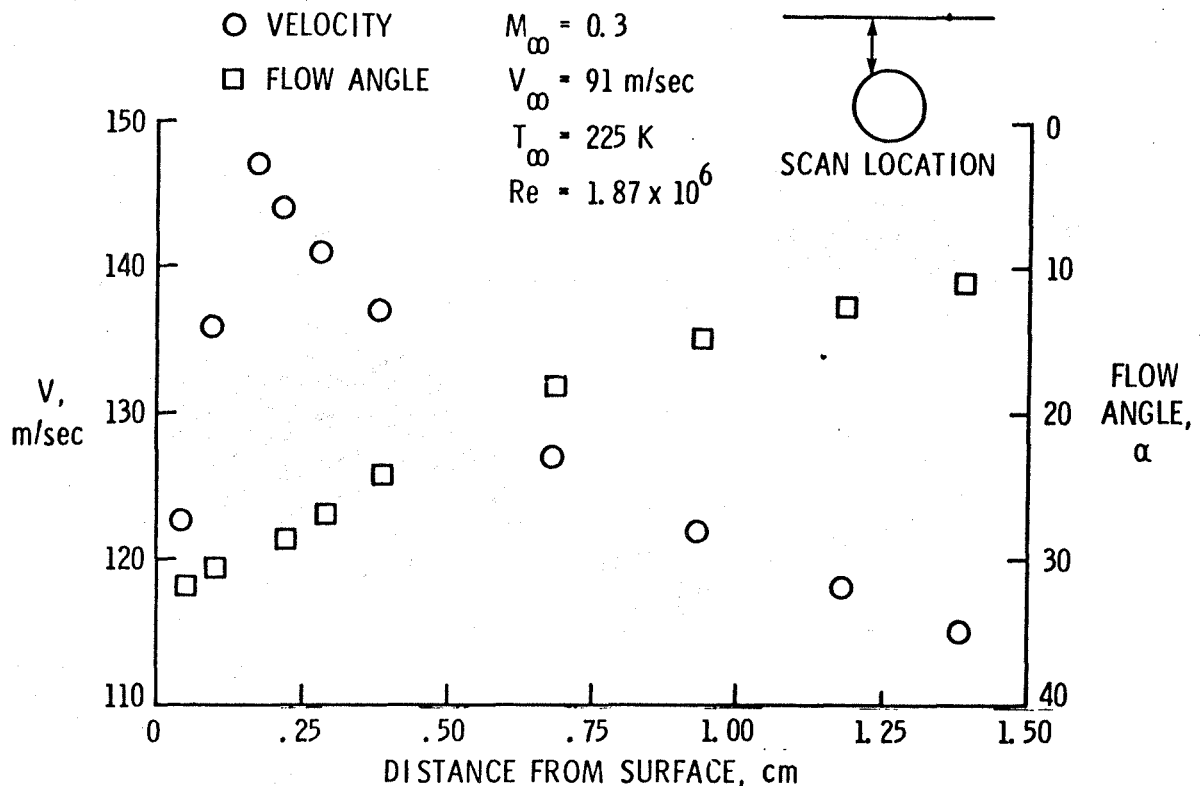
Skin friction measurements

Skin friction measured on the tunnel wall in cryogenic flow using UTSI moving belt balance.

Tunnel wall boundary layer studies

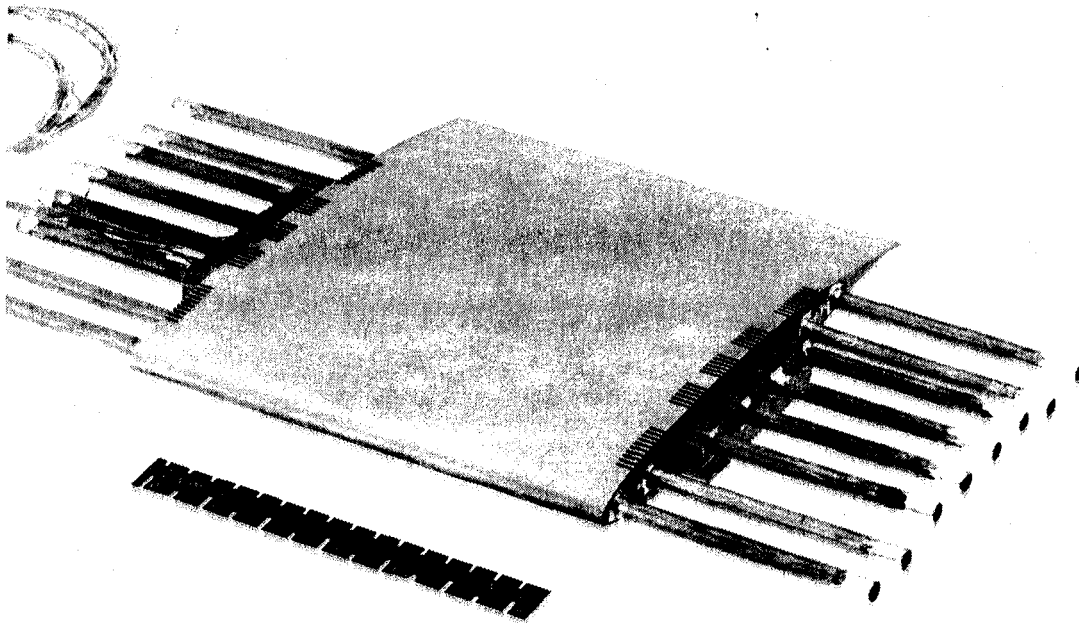
Boundary layer surveyed by pitot rake over a wide range of Reynolds number. Plots of displacement thickness and momentum thickness follow.

BOUNDARY LAYER SURVEY — 1.2 INCH CYLINDER 0.3m TCT



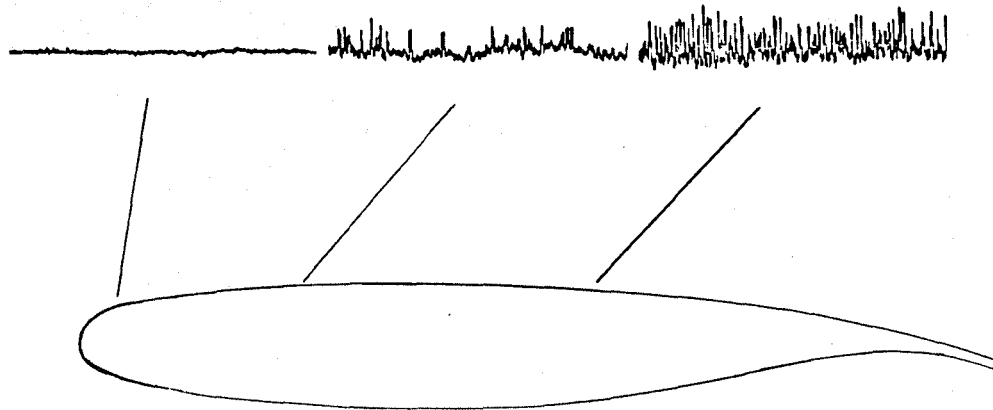
Use of a Two-Spot Laser as a Boundary Layer Probe

The two-spot laser, or more properly the Laser Transit Anemometer, LTA, focuses two laser beams into spots only 9 microns in diameter with a spot-to-spot separation of about 20 spot diameters. When the spots are aligned with the flow in a wind tunnel, that is, one spot upstream of the other, any reflective particle in the flow that happens to pass through the upstream spot will reflect back a pulse of light. As the particle passes through the second spot it will reflect back a second pulse of light. Since the distance between the spots is known, a measurement of the time between the two pulses yields velocity. This process may be greatly enhanced by seeding the flow with appropriate particles. The above data was generated by such a process where the LTA was used to survey the flow field of a cylinder along the line indicated in the "scan location" inset. This data is unique in that it was taken in a cryogenic environment and is one of the first successful attempts at measuring points in the boundary with this type of device. The two decreasing velocity points nearest the cylinder surface are in the boundary layer. For further details see reference 16.



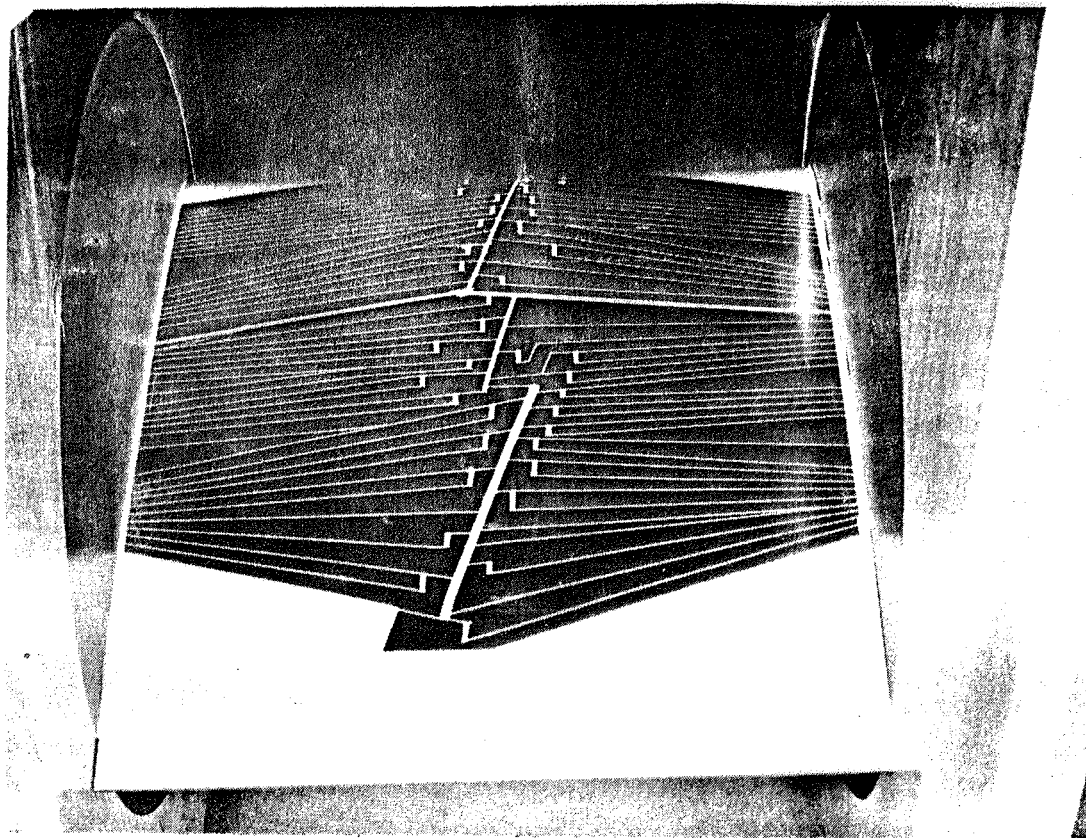
Nonadiabatic Airfoil Testing

The coupling of transonic flow and heat transfer has potential benefits both in flow control and to enhance our understanding of fluid mechanics. The case of the model cooler than the flow is of particular interest, but the experiment is difficult in a conventional tunnel due to the formation of ice. In the cryogenic tunnel however, the working fluid is nitrogen and there is no water vapor to condense on the model. Testing is conducted by operating the tunnel well above the temperature of liquid nitrogen and, by flowing liquid nitrogen through the tubes shown in the photograph, it is possible to maintain the model surface at a much lower temperature. The model is constructed of beryllium-copper, which has a very high thermal conductivity, to aid in maintaining nearly uniform surface temperatures in the presence of heat transfer from the test flow.



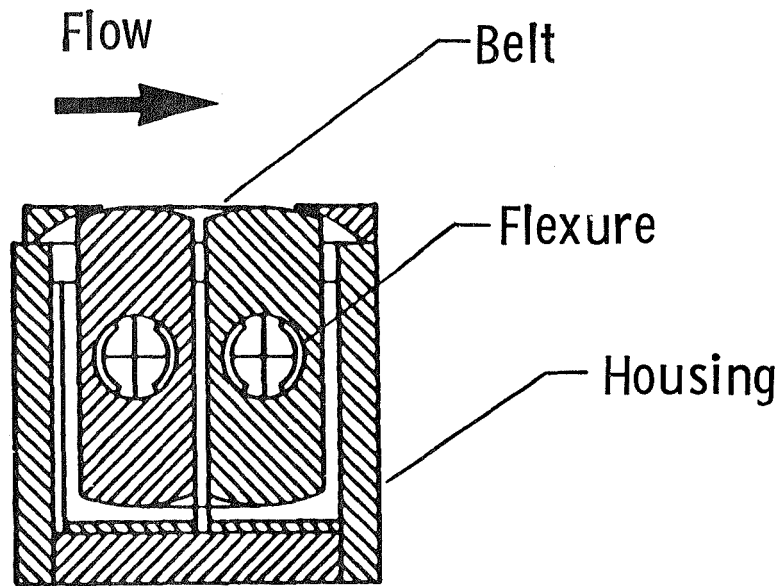
Transition Location by Fluctuating Pressure Measurement

The airfoil outline shown above is of a 14 percent thick supercritical airfoil recently tested in the 0.3-m TCT. This two-dimensional model was largely hollow and contained 43 transducers capable of measuring fluctuating pressures. The three traces shown above the airfoil are typical of the output data from these transducers. The trace at the left is near the nose of the model, has a low length Reynolds number, and exhibits a low amplitude fluctuating pressure trace typical of laminar flow. The center trace is from a transducer measuring pressures further back on the airfoil and produces a trace typical of transitional flow with a higher fluctuating amplitude as background and with superimposed turbulent precursor bursts of much higher amplitude. The trace at the right is well into fully developed turbulent flow characterized by high amplitude, high frequency fluctuations in pressure.



Transition Detection Using Hot Films

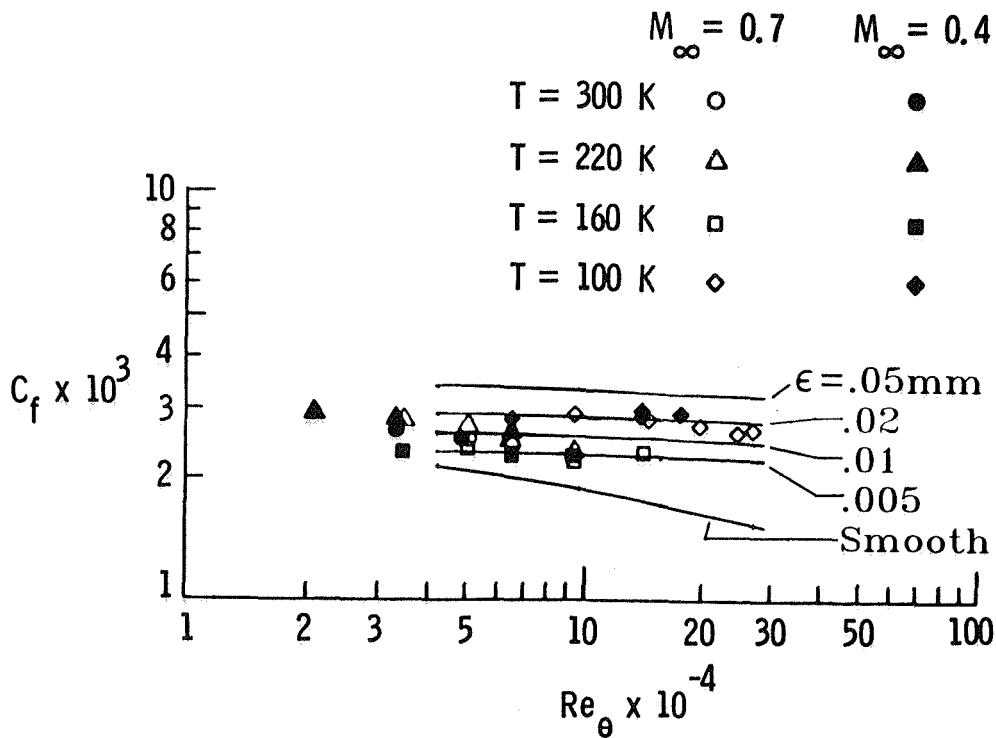
Photograph shows airfoil model mounted in the 0.3-m TCT with chordwise rows of hot-film gages mounted on the top surface. Gage technique was developed by the Douglas Aircraft Corporation and tested in a cooperative program with the Experimental Techniques Branch, NASA Langley. Method is based on peak heat transfer rates occurring at the beginning of fully turbulent flow. The visible parts of the gages are actually the plated-on connecting leads; the hot, sensitive portion of the gage is too fine to be visible in this photograph. More details may be found in reference 36.



Skin Friction Balance

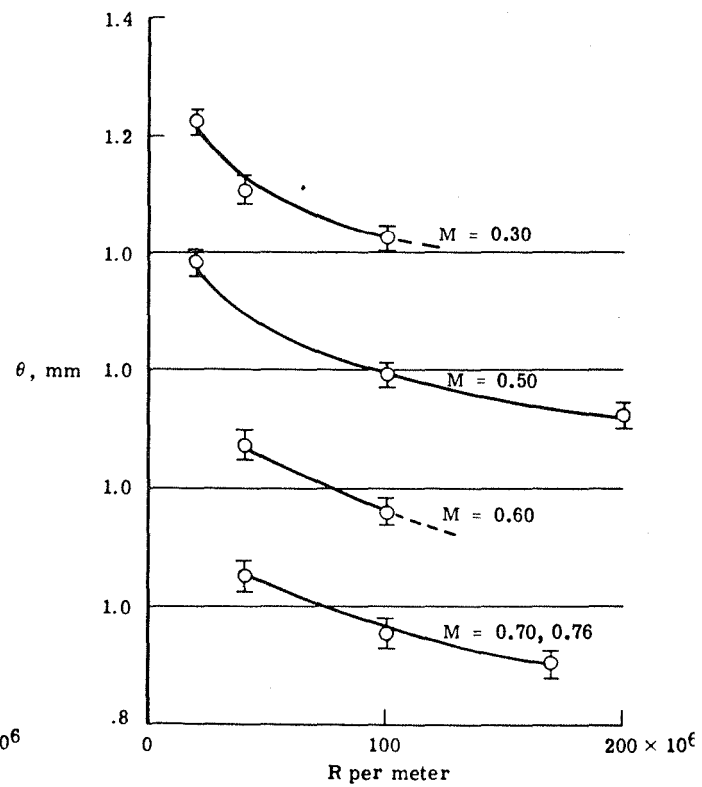
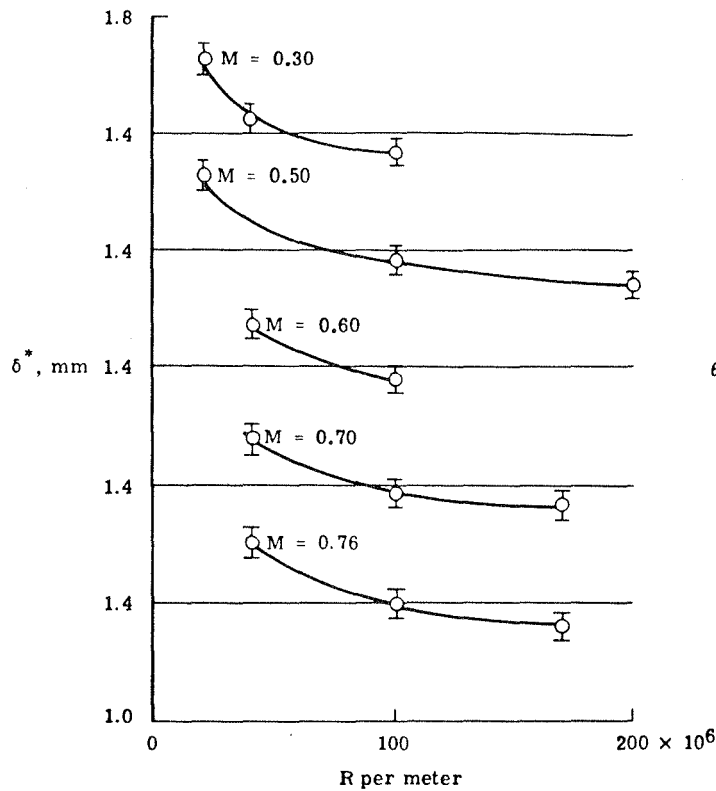
A skin friction balance has been developed by the University of Tennessee Space Institute, with the cooperation and support of the Experimental Techniques Branch, NASA Langley, for use in cryogenic environments. The balance uses a belt supported by two flexures to measure shear force. Figure 17 is a section drawing of the device indicating the location of the flexures and the belt. Movement of the belt results in rotation of the flexure. Strain gages mounted on the webs of flexures provide a voltage output proportional to the load on the belt. The entire device is mounted to position the belt flush with the surface of interest.

An interesting potential of this balance occurs with the substitution of a fiber optic pickup for the more usual strain gages. The optical pickup reads the movement of the belt directly, eliminating the need to install the strain gages on the interior of the flexure. This removes the barriers to miniaturization of the balance, and it is conceivable to reduce the linear dimensions by roughly an order of magnitude. Such a miniaturization would allow the installation of several balances in an airfoil model. These figures and further details may be found in reference 31.



The data shown in this figure was taken during a special test designed to evaluate the performance of several skin friction measurement devices in a cryogenic, high pressure, transonic environment. To insure a minimum of disturbance during these tests, there was no model mounted in the tunnel, and extra time was allowed for data acquisition to minimize temperature gradients. The skin friction measurements were taken on the tunnel sidewall, and special care was used in fitting the sidewall components to minimize boundary layer disturbances. However, the data exhibits a rough wall trend, i. e., very little change in C_f with increasing Reynolds number. It is instructive to consider the distributed wall roughness height which might predict the observed data. Curves representing a range of values for roughness height are plotted in the figure, and values in the range from 0.005 to 0.02 mm (0.0002 to 0.0008 inches) are typical of the data.

Even though joints between component parts are being represented by a distributed sand type roughness in this analysis, it is obvious that small disturbances will produce the trends shown by the data. When considering that this data was taken over large changes in temperature and pressure, which would cause small changes in the relative positions of the components, it is not surprising that the lowest temperatures lie in a band unto themselves. Finally, the classic approximation for smooth wall skin friction is shown, and is seen to approach the measured data at the lower Reynolds numbers which were obtained at conditions near atmospheric pressure and ambient temperature. Further details may be found in reference 31.



Tunnel Wall Boundary Layer Studies

The two curves presented here are momentum thickness and displacement thickness of the 0.3-m TCT test section wall boundary layer as a function of Reynolds number, and for selected Mach numbers. The displacement thickness is delta star, and the momentum thickness is theta. These boundary layer properties were calculated from pitot pressure surveys taken by a miniature 16 probe rake mounted on the tunnel sidewall. These charts and more detailed information may be found in reference 23. The significance of this data is that it covers such a wide range of Reynolds number and provides an input to wall interference prediction codes.

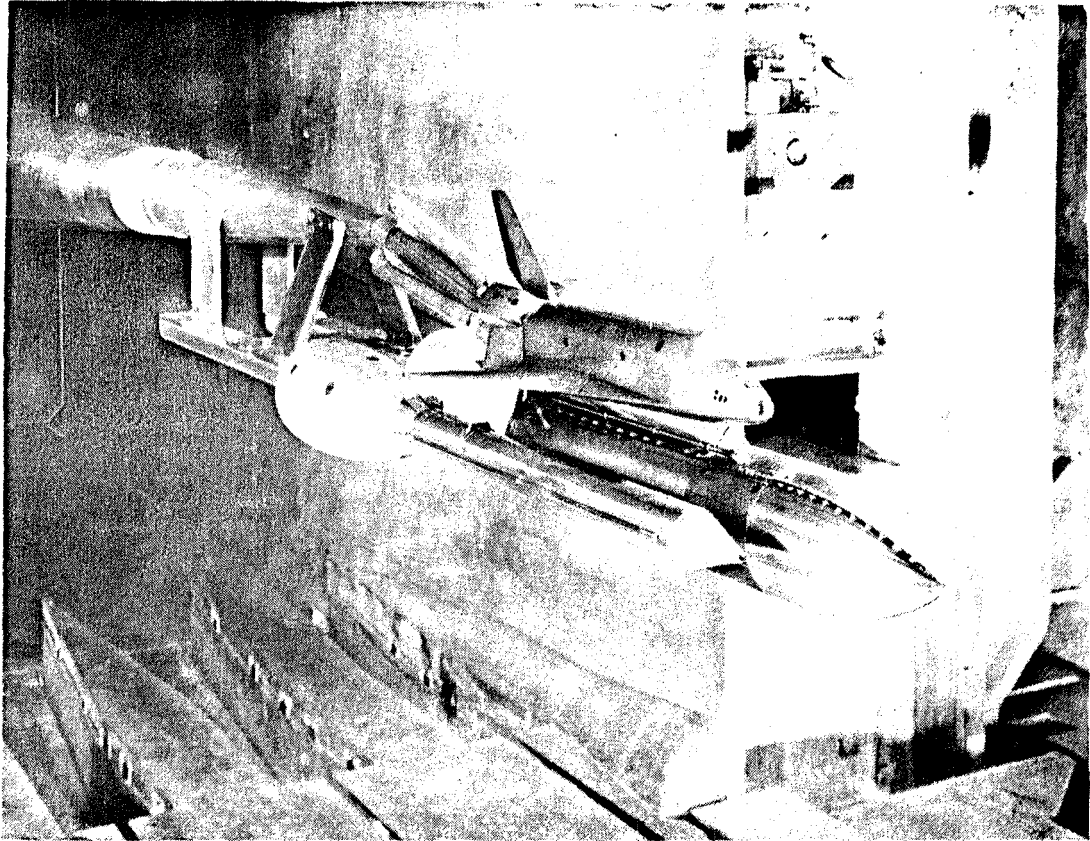
Recent Progress in Cryogenic Test Techniques Testing in the National Transonic Facility

Three dimensional one percent Shuttle tested in full ascent configuration

Photograph follows.

Transport configuration, "Pathfinder I", testing involving force and pressure measurement

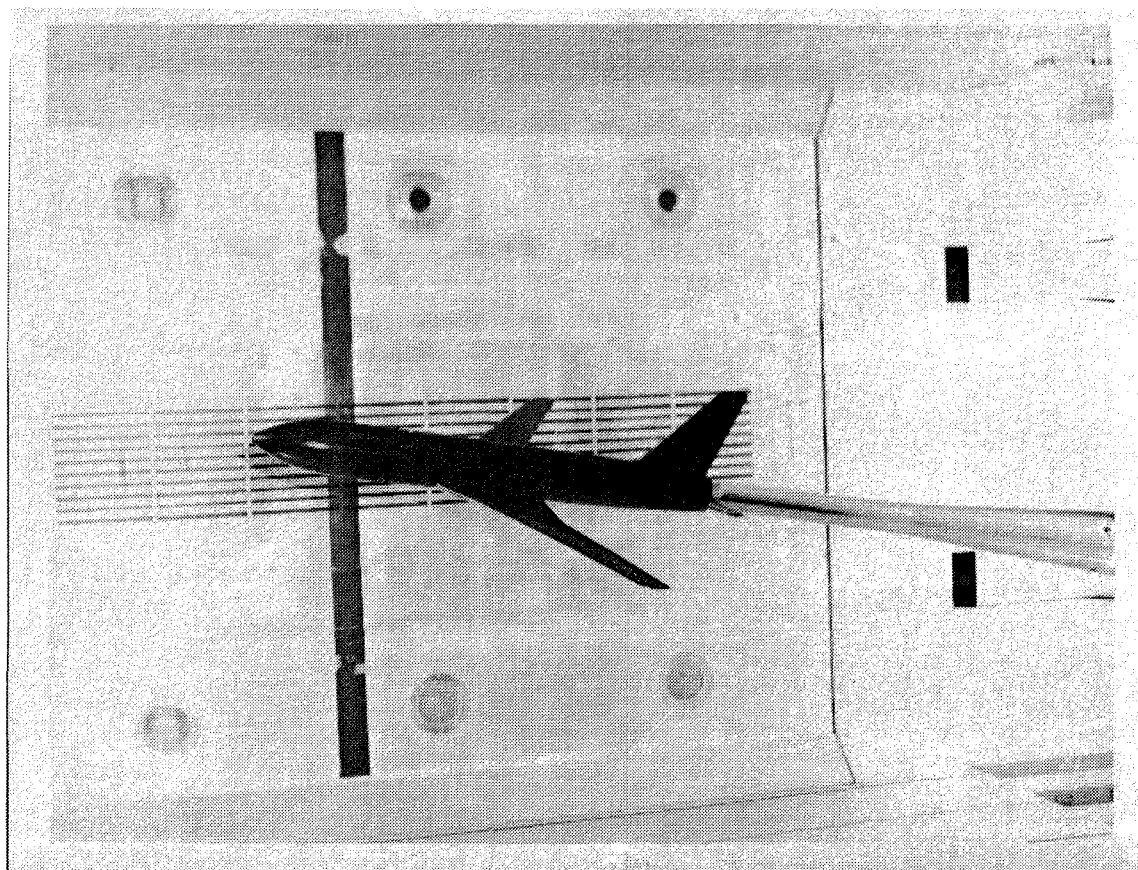
Photograph follows.



Shuttle Launch Configuration

The cryogenic test technique illustrated here is that of a fully pressure-instrumented three dimensional model used in one of the initial tests in the National Transonic Facility. The model shown is the Space Shuttle in detailed ascent configuration and it is easily the most elaborate cryogenic model tested to date. The largest component is the hydrogen fuel tank; the Orbiter is mated directly to this tank and the solid rocket boosters are attached to either side of the tank. One of the boosters is hidden in this view. The large, ogive shaped bodies attached to the base of each booster are the aerodynamic equivalent of the exhaust plumes at transonic conditions. The three more cylindrical bodies attached to the base of the Orbiter represent the plumes of the Orbiter's Hydrogen fueled engines.

Note the elaborate modeling detail such as the tank structure, the Orbiter cockpit windows and the control rocket exhaust ports. These observations teach a lesson about high Reynolds number testing in that full simulation to obtain very correct flight fluid mechanics also requires full attention to detail in all other aspects of the test, including the modeling of the configuration.



Commercial Transport Test in the NTF

"Pathfinder I", a representative advanced commercial transport model, is shown mounted in the National Transonic Facility test section. The model is mounted on a 6-component strain gage balance and is also equipped with an internal pressure scanning device. Model is painted dark blue to provide contrast to white targets mounted on the wing. The targets are part of an optical system to measure the amount of wing deflection under load. These measurements will aid in the determination of aeroelastic effects on performance. The independent measurement of Reynolds number related and aeroelastic effects is a task for which this facility is uniquely well suited.

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16. Abstract <p>This paper is a compilation of lectures presented at various Universities over a span of several years. A central theme of these lectures has been to present the research facility in terms of the service it provides to, and its potential effect on, the entire community, rather than just the research community. This theme is preserved in this paper which deals with the cryogenic transonic wind tunnels at Langley Research Center. Transonic aerodynamics is a focus both because of its crucial role in determining the success of aeronautical systems and because cryogenic wind tunnels are especially applicable to the transonics problem.</p> <p>The paper also provides historical perspective and technical background for cryogenic tunnels, culminating in a brief review of cryogenic wind tunnel projects around the world. An appendix is included to provide up to date information on testing techniques that have been developed for the cryogenic tunnels at Langley Research Center. In order to be as inclusive and as current as possible, the appendix is less formal than the main body of the paper. It is anticipated that this paper will be of particular value to the technical layman who is inquisitive as to the value of, and need for, cryogenic tunnels.</p>					
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